

NEXT MEETING, APRIL, 22 1904.

Subject : ALTERNATING-CURRENT GENERATORS. Papers to be discussed are printed in this issue of the Transactions. See pages 145-214.

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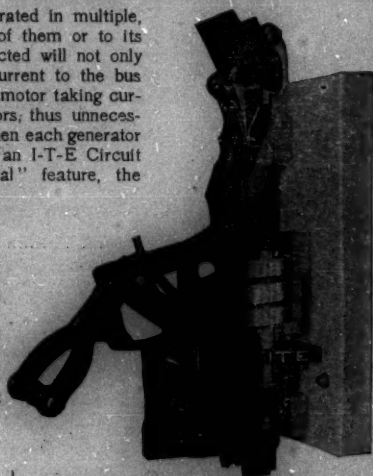
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STRIKE, ROBERT JOHN, Mains Engineer and Technical Assistant, The Launceston Corporation, Town Hall, Launceston, Tasmania.	J. T. Wolfe. A. W. Jones. H. R. Harper.
TAYLOR, WILLIAM ARTHUR, Electrical Engineer, Standard Telephone and Electric Co., res., 408 W. Mifflin St., Madison, Wis.	B. V. Swenson. D. C. Jackson. G. C. Shaad.
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TERVEN, LEWIS AUGUSTUS, Electrician, Nernst Lamp Co., Pittsburg, Pa.	A. J. Wurts. D. C. Jackson. L. K. Comstock.
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ZUCKER, ARTHUR A., Draftsman, N. Y. C. & H. R. R. Co.; res., 308 W. 94th St., New York City.	L. W. Rosenthal. J. D. Keiley. E. B. Katte.

And the following Associates were transferred to the grade of Member.

- ARTHUR HILLYER FORD, Professor of Electrical Engineering, Georgia School of Technology, Atlanta, Ga.
 FREDERICK GEORGE PROUTT, Electrical Engineer, Memphis Consolidated Gas and Electric Co., Memphis, Tenn.

SPEED-TORQUE CHARACTERISTICS OF THE SINGLE-PHASE REPULSION MOTOR.

BY WALTER I. SLICHTER.

The single-phase commutator motor has attracted considerable attention of late, as there is quite a demand in railway work as well as in numerous other lines for an alternating-current motor that will start under a heavy load with a reasonable consumption of energy. At present it appears that a commutator motor is the only type that will fulfil these conditions.

For some months past the writer of this paper has been in charge of a series of experiments with various types of alternating-current commutator motors. During these experiments much attention was given to the repulsion motor. It is the purpose of this paper to place before the INSTITUTE some of the results obtained, and to point out some of the characteristics of the motor which give promise of making it a very prominent factor in some lines of electric railroading of the future.

For the benefit of those not already familiar with this type of motor, it may be here stated that it is a single-phase commutating motor, resembling very much a regular direct-current armature in an induction-motor field. The resemblance to the induction motor is carried still further in that there is no electrical connection between the primary and secondary. This makes it possible to wind the primary for a high line voltage, while the voltage of the secondary winding is chosen at such a value as may be commutated satisfactorily, since it is short circuited on itself through its brushes.

The motor has the same characteristics as the direct-current series motor; namely, maximum torque at starting, increasing torque with increasing current and decreasing speed, and comparatively constant efficiency through a wide range of speed.

The maximum speed of the motor is limited only by the load and impressed voltage and has no relation to the synchronous speed.

Due to the reactance of the motor circuits, the power-factor at starting is low and will be with any alternating-current motor; but in the repulsion motor a low power-factor does not mean small torque. On the contrary, the maximum torque occurs simultaneously with the lowest power-factor; that is, at starting. The power-factor of the repulsion motor rises very rapidly with the speed; it reaches a good value at one-third synchronous speed, and values near to 90 per cent are obtained over a considerable range of speed. For this reason a large number of poles is not necessary and frequencies of 25, 40, and even 60 cycles may be employed.

The rotating conductors of the secondary cutting the primary flux generate a leading e.m.f., which causes a leading current to flow therein and gives the high power-factor of the motor. In the plain repulsion motor, this leading current never reaches a value great enough to compensate entirely for the magnetizing and other wattless currents at available speeds, but the phenomenon is utilized to obtain unity power-factor in the compensated type by the addition of a second circuit. The inherently good power-factor of the repulsion motor makes it possible to use larger clearance between field and armature than is permitted in induction motors, thus greatly increasing its value in railway work where comparatively large air-gaps are necessary.

The curves given are partly from test and partly from calculation of motors having air-gaps of 0.125 inch on a side, and more. The air-gap of corresponding stationary induction motors would be 0.040 inch and more.

The efficiency, while not so good as in a direct-current motor, is yet very good, reaching values of from 80 to 85, including gear-loss for sizes ranging from 50 to 200 horse-power.

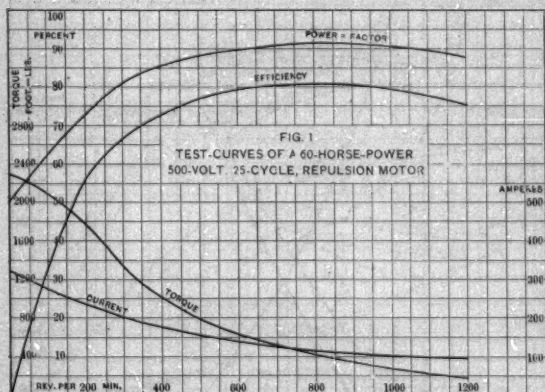
Commutation at normal speeds is inherently good, due to the revolving field. As the speed decreases, the current increases rapidly, producing a tendency to spark, but with the reduced voltage of starting the rush of current is limited to values within the range of good commutation, as in the direct-current motor.

At higher speeds, ranging above one-and-a-half times synchronism, the frequency of commutation becomes high and sparking appears.

The motor of Fig. 1 will start with 75 per cent of full

voltage and twice full-load current with no trouble from sparking. As these curves are prepared upon a railway-motor basis, and full-load current will produce a rise of 75° C. after one hour's run, the ability of the repulsion motor successfully to commutate overloads is equal to that of the direct-current series motor; in fact, better, due to the short-circuited commutator which makes flashing-over impossible.

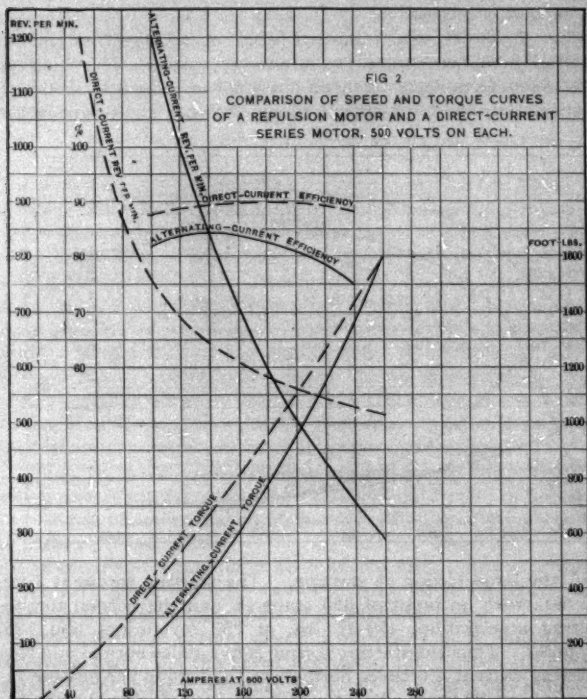
Fig. 1 shows the characteristics of a repulsion motor plotted with revolutions per minute as a base. These curves are taken from tests on a 60-horse-power, 25-cycle, 500-volt motor; they show the rapidly rising efficiency and power-factor



and the large torque at starting. The starting torque is 2300 ft. lbs., with an input of 325 amperes, and the normal torque during acceleration, 450 ft. lbs. at 750 revolutions and 125 amperes. Thus the starting torque is five times normal and the starting current 2.6 times normal; or the torque per ampere at starting is 1.92 times what it is at normal speed, should occasion demand the full starting capacity of the motor.

This gives an idea of the steep speed-characteristics of the motor, which are even better shown in Fig. 2. The full lines refer to a later type of repulsion motor and the broken lines to a standard direct-current series railway motor; these curves are plotted in the usual way with current as a base.

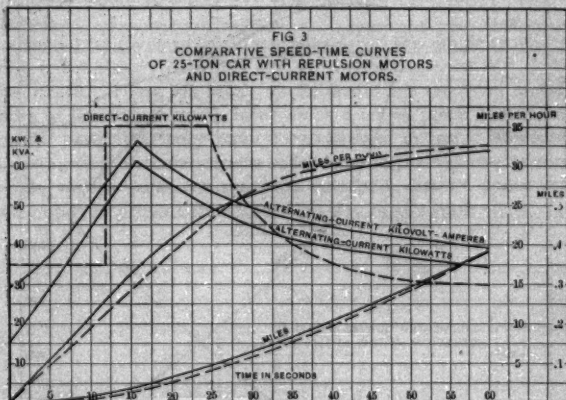
This shows that the torque increases more rapidly with increasing current in the repulsion motor than in the series; and conversely that the speed of the repulsion motor increases more rapidly with decreasing current than in the series motor. Efficiency, including gear-loss, is given and is 84.5 per cent at the



maximum for the alternating-current motor. This motor was designed with the steep speed-characteristics for acceleration work, while the motor of Fig. 4 is designed for constant-speed running and has not such steep curves but better constants at light loads.

The characteristics show the repulsion motor to be admirably adapted for acceleration work, the efficiency of acceleration being higher than in direct-current work, due to the possibility of obtaining fractional e.m.f.s with alternating currents without introducing the dead resistance losses of the direct-current system of control.

This is shown in the curves on Fig. 3, which gives the acceleration curves from test of a 25-ton car equipped with two 60-h-p. repulsion motors. The full lines indicate the repulsion motor characteristics and the broken lines those calculated for a direct-current equipment. The gearing is chosen for the same

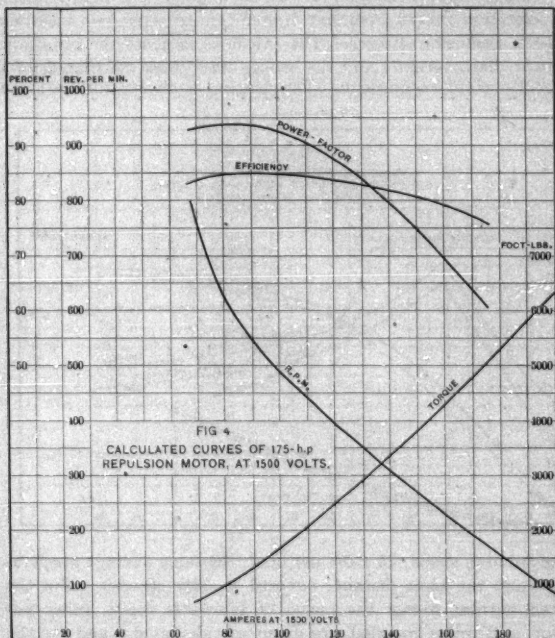


free-running speed, 33 miles per hour, the same average acceleration, and the same distance covered in sixty seconds. For the direct-current motor the curve of kilowatts input, miles per hour, and miles traveled, are given as calculated; and for the alternating-current motor the kilovolt-ampere input, kilowatt input, miles per hour, and miles traveled, from test.

The repulsion motor remains on the controller only 16 seconds and the direct-current motor 25 seconds. The maximum power taken by the direct-current motor is 70 kw. and by the repulsion motor 61 kw. or 67 kilovolt-amperes. At the end of 25 seconds, the total kw-hour input in the two cases is 0.375 for the direct current and .30 for the alternating current. At the

end of 60 seconds both cars have covered a distance of 0.039 mile and have reached practically the same speed of 32.5 miles per hour, the kw.-hour input being 0.72 for the direct current and 0.685 for the alternating current.

By comparing the areas of the kilowatt curves in the two cases the gain or rather the saving by the use of the alternating cur-



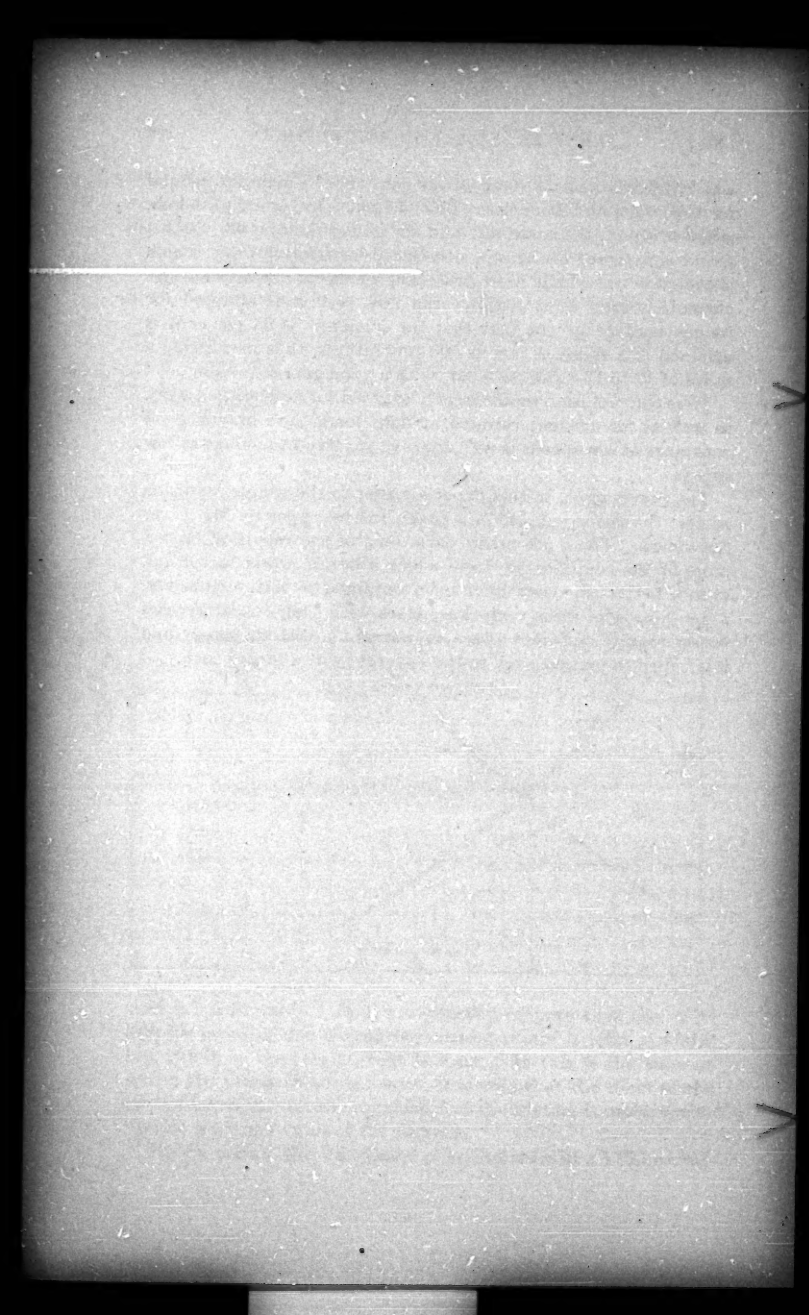
rent is readily seen. It is also worthy of note that the volt-ampere input of the alternating-current motor is least at starting; that is, the line current is least. As this is the time at which the power-factor is lowest, it is seen that the effect of the low power-factor on the regulation of the system is much modified by the small value of the current.

Fig. 4 shows the calculated characteristics of a 175-hp. rail-

way repulsion motor having an air-gap of 0.15 inch and wound for 1500 volts and 25 cycles. The efficiency, including gear-loss, is 85 per cent at the maximum and the power-factor is 93. Such a motor is designed for heavy, slow-speed locomotive work, which is probably one of the most promising fields for the alternating-current motor. It is readily seen how well it is adapted for freight haulage by the fact that the efficiency of 85 per cent is attained at a speed as low as 500 revolutions, thus permitting a speed of 12 to 15 miles per hour, with a good gear reduction.

Thus the repulsion motor is well adapted for acceleration work as well as for efficient running at light loads, and having good constants at low speeds is well adapted for freight haulage at low speeds.

The curves given in this paper all refer to the simple repulsion motor, the theory of which is given in the paper by Mr. C. P. Steinmetz. There are many variations of the repulsion motor, more or less complicated, from which a better power-factor and even a better efficiency have been obtained in test. However, a description of these various schemes with their characteristics would require sufficient space to warrant a distinct paper and it is hoped to present such to the INSTITUTE at a future date.



THE ALTERNATING-CURRENT RAILWAY MOTOR

BY CHARLES P. STEINMETZ.

For electric railroading a motor is required which maintains a high value of efficiency over a wide range of speed. That is, the torque per ampere input at constant impressed voltage must increase with decrease of speed, the speed increase with decrease of load.

In electric motors, torque is produced by the action of a magnetic field upon currents flowing in an armature movable with regard to the field. If then the field is constantly excited—shunt motor on constant potential—the torque is approximately proportional to the current, the speed approximately constant at all loads. If the field is excited by the main current of the motor—series motor on constant potential—the field strength and thereby the torque per ampere varies approximately proportional to the current, and thereby the load, the whole torque approximately proportional to the square of the current and the speed inversely proportional to the current, leaving saturation out of consideration. That is, the motor has the characteristic specified above for a railway motor.

Since the direction of rotation of the direct-current motor is independent of the direction of the impressed e.m.f., with laminated field the direct-current motor can be operated with alternating currents. By the use of alternating currents it becomes possible to transfer current from circuit to circuit by induction, and instead of passing the main-line current through the armature of the alternating-current motor, the armature-circuit can be closed upon itself and the current induced therein as transformer secondary by a stationary primary coil in the main circuit surrounding the armature.

Condition of operation of the direct-current motor type on

alternating current is, however, that the current in field and armature reverses simultaneously. This is by necessity the case in the series motor. In the shunt motor, however, the armature current as energy current should be in phase with the impressed e.m.f., while the field current as magnetizing current lags nearly 90° . To bring it back into phase, W. Stanley tried condensers in series in the field circuit, but failed, due to the impossibility of neutralizing the self-induction of the field which varies with the commutation and the frequency, by the negative self-induction of the condensers, which varies with the frequency in the opposite direction. The solution of the problem has been found by the use of polyphase systems, by utilizing for the field excitation an e.m.f. in quadrature with the armature currents acted upon by the field magnetism. As I have shown elsewhere, the polyphase induction motor can be considered as a development of the direct-current shunt motor for alternating-current circuits, and indeed has all the shunt motor characteristics regarding speed, torque, etc. As railway motor the induction motor has therefore not been exploited, although it has been strongly recommended in those very few cases where it appeared good engineering. Experimental work with polyphase induction motor railways has been carried on continuously since 1893.

While in the early days of alternating-current motor development, all other engineers were industriously developing the constant-speed stationary motor type, with shunt motor characteristic, only Rudolph Eickemeyer of Yonkers was far-sighted enough to realize the vast future of alternating-current railroading, and to appreciate the absolute necessity of the series motor characteristic for railway work, and undertake the development of the single-phase alternating-current series motor. I had the good fortune at that time to be associated with Mr. Eickemeyer.

As was pointed out by G. Kapp, I believe in 1888, the power-factor of the alternating-current series motor is inherently low, since the same magnetic flux which induces, proportional to the frequency of rotation, the e.m.f. of useful work in the armature conductors, induces in the field coils an e.m.f. of self-induction, proportional to the frequency of alternation. Hence, giving the armature the same number of turns as the field (which is more than permissible in good practice, since good practice requires weak armature and strong field), even at synchronous speed the e.m.f. of rotation of the armature would still only be

equal to the e.m.f. of self-induction of the field; and the power-factor, allowing for an additional self-induction of the armature, would be below 70 per cent. This probably deterred the other engineers from considering the alternating-current series motor.

Eickemeyer solved the difficulty by designing the armature with a number of turns several times greater than the field (24 to 7 in the first motor built) and neutralizing the armature self-induction and reaction by a stationary secondary circuit surrounding the armature at right angles electrically to the field circuit (the "cross-coil," as he called it), and either short-circuited upon itself or energized by the main current in opposite direction to the current in the armature.

In January, 1891, I tested the first motor of this type, a bipolar motor with the following constants:

Field: Two coils of 14 turns No. 10 B & S wire, connected in parallel.

Armature: 24 coils of four turns each of No. 12 B & S wire.

Secondary circuit: Two coils of 18 turns each of No. 10 B & S wire connected in parallel.

At 100 cycles and 150 volts impressed e.m.f., this motor gave at three-fourths synchronous speed:

Current: 45 amperes.

$I^2 R$: 400 watts.

Hysteresis and eddy currents: 900 watts.

Total output, including friction: 4000 watts.

Hence:

Efficiency, 75.5 per cent.

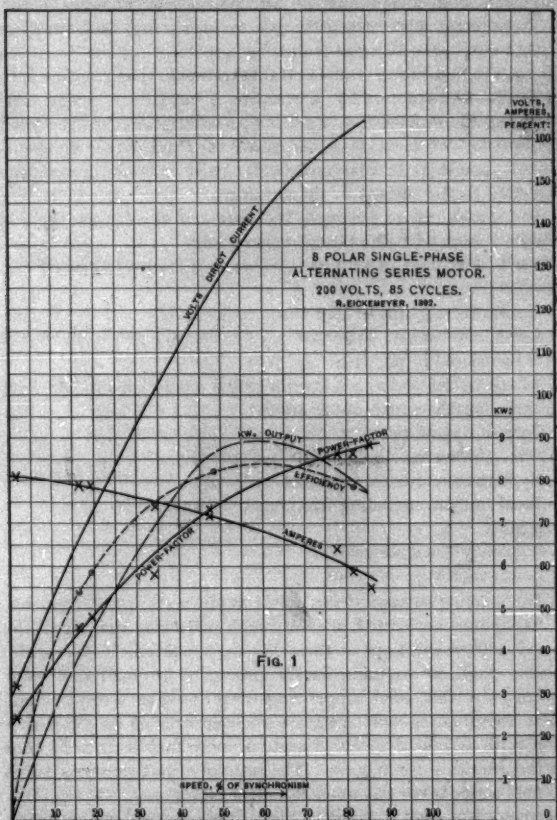
Power-factor, 79 per cent.

The starting current of this motor at 150 volts was 70 amperes.

As bipolar motor with the very high frequency then used, the speed, 4500 revolutions at three-fourths synchronism, was undesirably high, so we immediately proceeded to build an 8-polar motor. In this, solid copper rings were used as secondary circuits surrounding the armature and neutralizing its self-induction, with an effective copper-section more than four times that of the armature conductors. The ratio of armature series turns to field series turns was about 4. This motor was tested in 1892. The record of tests is given in Fig. 1, the observed values being marked on the curves. For comparison on this sheet is also given the direct-current voltage required to operate this motor at the same speed and current.

As seen, when approaching synchronous speed, the power-

factor is nearly 90 per cent. The commutation was fair at 85 cycles, the highest frequency at which our factory engine was able to drive the alternator, and perfect at 33 cycles.



A number of railway motors of this type were designed. The great difficulty, however, was that during these early days 125 to 133 cycles was the standard frequency in this country, 60 cycles hardly considered, and 25 cycles not yet proposed.

The efficiency of this alternating-current series motor is slightly lower than that of the same motor on direct-current circuit, due:

1. To the hysteresis loss in the field.
2. The hysteresis loss in the armature core, which is of full frequency up to synchronism and of still higher frequency, the frequency of rotation, beyond synchronism.
3. The I^2R loss in the short-circuited secondary conductors surrounding the armature.

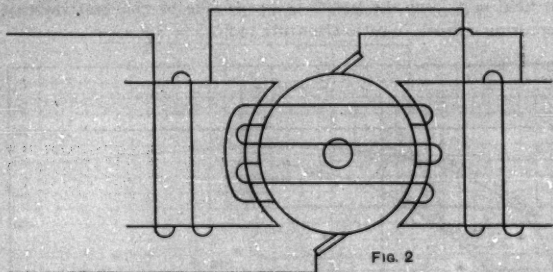


FIG. 2

As seen, to make the alternating-current series motor practicable, the transformer feature must be introduced, by having its armature as primary circuit closely surrounded by a short-circuited secondary circuit, as shown diagrammatically in Fig. 2.

Instead of closing the stationary circuit upon itself as second-

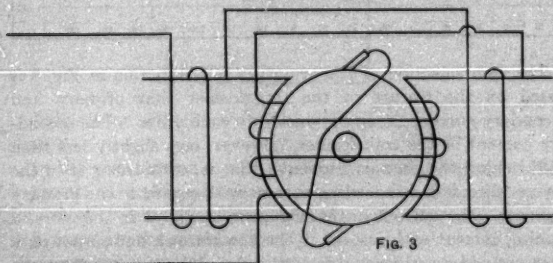


FIG. 3

ary circuit and feeding the main current into the rotating armature as primary circuit, mechanically the same results would obviously be obtained by using the stationary circuit as primary energized by the main current, and closing the armature upon itself as secondary by short circuiting the brushes and thereby

keeping the main current and the line potential away from the armature, as shown diagrammatically in Fig. 3. This introduces the great advantage of reversing the sign of the uncompensated part of the armature self-induction, so that it is subtractive, which results in an essential improvement of the power-factor, especially at low speed.

This is shown in Fig. 4, where with the speed as abscissas, in per cent of synchronism, are plotted the power-factor of the Eickemeyer compensated series motor of Fig. 1, of ratio armature to field = 4, and the power-factor of one of the first railway repulsion motors, of ratio armature to field = 3.5.

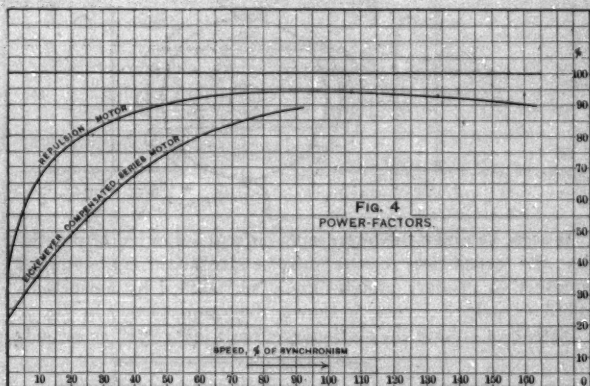


FIG. 4
POWER-FACTORS.

The compensation of the armature self-induction in Fig. 3 is based on the feature of the transformer that primary and secondary current are in opposition to each other. The secondary current of the transformer, however, lags slightly less than 180° behind the primary current; that is, considering it in the reverse direction, is a leading current with regard to the primary current. The current in the armature in Fig. 3 is, therefore, a leading current with respect to the line current, and so not only does not add an additional lag but reduces the lag caused by the self-induction of the field-exciting coil.

This motor then consists of a short-circuited armature surrounded by two coils at right angles with each other and connected in series, as illustrated in Fig. 5; the one, A_1 , parallel

with the effective armature circuit, acting as primary of a transformer to induce the secondary armature current; the other, A_1 , the field-exciting coil. The ratio of turns of these coils, n_2 , to n_1 , is the ratio of effective armature series turns to field turns, as discussed before. Obviously, these two coils can be replaced by one coil at an angle with the position of brushes as shown in Fig. 6, and the cotangent of the angle of the axis of this coil with the position of the brushes is above ratio; that is, the smaller this angle the greater is the ratio of armature to field turns; that is, the better the power-factor of the motor.

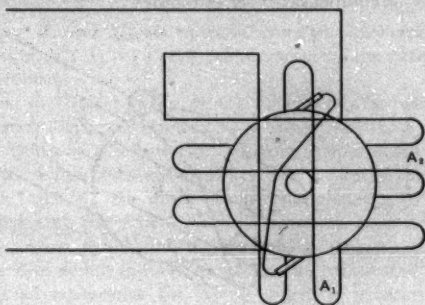
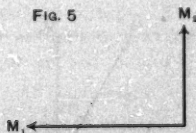


FIG. 5



This motor, Fig. 6, is Professor Elihu Thomson's repulsion motor.

In the armature an e.m.f. is induced by the alternation of the magnetic field, M_2 , of coil A_2 , proportional to M_2 and to the impressed frequency and in quadrature with M_2 ; and an e.m.f. is induced by the rotation through the magnetic flux M_1 of coil A_1 , proportional to M_1 and to the frequency of rotation and in phase with M_1 . These two e.m.fs. must be equal and opposite, since the armature is short circuited (neglecting the resistance and self-inductive reactance of the armature), and at synchronism, M_1 and M_2 are, therefore, equal and in quadrature with

each other; that is, in the armature of the motor, Fig. 5, and therefore of the repulsion motor, Fig. 6, at synchronism a uniform rotating field exists and the hysteresis loss in the armature core is therefore zero at synchronism and at other speeds proportional to the difference between speed and synchronism; that is, to the slip, just as in the polyphase induction motor; while in the motor, Fig. 2, the hysteresis loss in the armature core is proportional to the impressed frequency or the frequency of rotation, whichever is the higher frequency. The hysteresis loss of the repulsion motor is therefore lower than that of the same motor as compensated series motor.

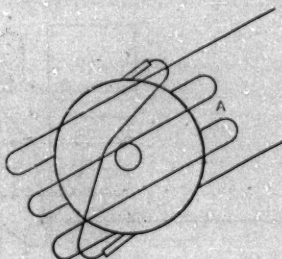
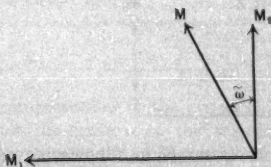


FIG. 6



In general, if in the repulsion motor in Fig. 6 the magnetic flux in line with the brushes, which does not induce e.m.f. by rotation but only by alternation, is denoted by M_2 ; the magnetic flux in quadrature with the brushes which induces e.m.f. in the armature by its rotation but not by the alternation of the flux, by M_1 ; and the magnetic flux in the axis of the primary coil A , which is much nearer to M_2 than to M_1 , since good power-factor requires a small angle ω , by M , the two e.m.fs. induced in the armature, by the rotation through the flux M_1 , are:

$$E_1 = 2 \pi N_0 M_1 n,$$

By the alternation of the flux M_2 ,

$$E_2 = -j 2 \pi N M_2 n$$

Where n = number of armature turns,

N = impressed frequency;

N_0 = frequency of rotation.

Since, approximately, $E_2 = E_1$, it is,

$$j N_0 M_1 = N M_2$$

or

$$j M_1 : M_2 = N : N_0 \quad (1)$$

That is: M_1 and M_2 are in quadrature in phase and the ratio of their intensity is inversely proportional to the ratio of speed to synchronism.

That is, in the repulsion motor an elliptically rotating field exists which becomes circular; in other words, a uniformly rotating field, at synchronism. Below synchronism the component M_1 , which induces e.m.f. by the rotation of the armature is greater than M_2 , the more the lower the speed. The flux M interlinked with the primary coil is, however, nearer to M_2 and therefore below synchronism, especially at low speeds, the magnetic flux which induces e.m.f. by the rotation of the armature and so represents the useful work, is greater than the magnetic flux which interlinks with the primary coil and so gives the lag of the primary current. This accounts for the high power-factor of the repulsion motor at low speeds.

Neglecting resistance and self-inductive reactance, it is,

$$M = \text{constant,}$$

corresponding to the impressed voltage.

From equation (1) it follows:

$$M_2 = j M_1 (N_0/N)$$

Hence,

$$\begin{aligned} M &= M_2 \cos \omega + M_1 \sin \omega \\ &= M_1 [\sin \omega + j (N_0/N) \cos \omega] \end{aligned}$$

$$M_1 = \frac{M}{\sin \omega + j (N_0/N) \cos \omega}$$

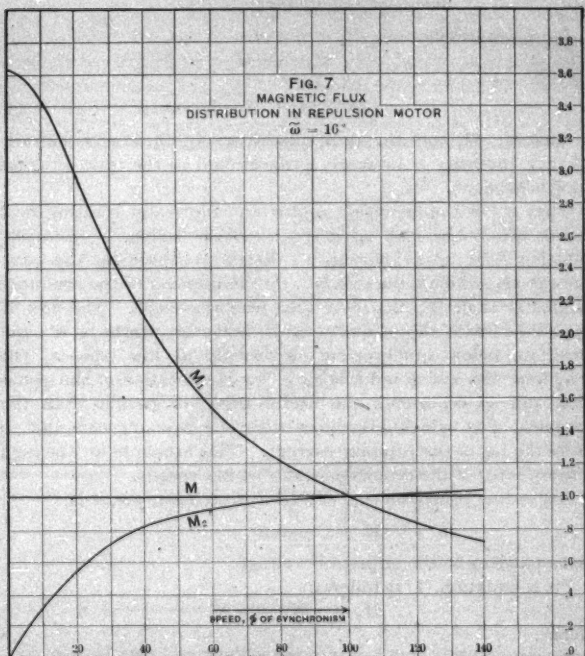
$$M_2 = \frac{M}{\cos \omega - j (N/N_0) \sin \omega}$$

(2)

or, absolute:

$$M_1 = \frac{M}{\sqrt{\sin^2 \omega + (N_0/N)^2 \cos^2 \omega}}$$

$$M_2 = \frac{M}{\sqrt{\cos^2 \omega + (N/N_0)^2 \sin^2 \omega}} \quad (3)$$



At synchronism: $N_0 = N$, it is:

$$M_1 = M_2 = M$$

At standstill: $N_0 = 0$, it is:

$$M_1 = \frac{M}{\sin \omega}$$

$$M_2 = 0$$

In Fig. 7 are shown the two quadrature components M_1 and M_2 of the magnetic field of the repulsion motor, for $\omega = 16^\circ$ and $M = 1.0$.

In the theoretical investigation and practical calculation of the repulsion motor, just as in the polyphase and single-phase induction motor, the transformer feature is made the starting point and the motor considered as a transformer, the secondary of which is standing at a constant angle ω with regard to the primary, so that motion results from the repulsive thrust existing between primary and secondary.

Let in vector denotation:

E_0 = impressed e.m.f., used as zero vector e_0 ;

I = primary current;

I_1 = secondary current reduced to the primary by the ratio of turns (the same as customary in induction motors);

Z = primary exciting impedance that is, primary induced e.m.f., divided by primary current at open secondary circuit;

Z_0 = primary self-inductive impedance;

Z_1 = secondary self-inductive impedance reduced to the primary circuit;

ω = angle between primary and secondary axis; that is, angle of shift of brushes from the position of complete transformer action;

$a = (N_0/N) =$ ratio of speed to frequency.

The total m.m.f. acting upon the primary coil is then: Primary current I plus component of secondary current acting in the direction of the primary, or $I_1 \cos \omega$.

Hence,

$$I + I_1 \cos \omega$$

This, then, is the primary exciting current; and the primary induced e.m.f. is therefore $(I + I_1 \cos \omega) Z$.

The primary impedance voltage is $I Z_0$.

Hence,

$$e_0 = Z (I + I_1 \cos \omega) + I Z_0.$$

In the secondary circuit an e.m.f. is induced by its rotation through the magnetic flux M_1 in quadrature with the secondary axis, which is in phase with this magnetic flux. This magnetic flux M_1 is due to the component of primary current acting in this direction: $I \sin \omega$, since the secondary current exerts no m.m.f. at right angles to the axis of the secondary coil. The e.m.f. induced thereby is in phase with I .

This e.m.f., induced by flux M_1 is therefore,

$$E_1 = a x I \sin \omega \quad (4)$$

In the secondary, an e.m.f. is induced also by the alternation of the magnetic flux M_2 in the axis of the secondary coil.

This magnetic flux is produced by the m.m.f. of the secondary current I_1 and the component of primary current acting in this direction: $I \cos \omega$, hence, due to

$$I_1 + I \cos \omega$$

and the e.m.f. induced hereby is

$$E_2 = -Z (I_1 + I \cos \omega)$$

The impedance e.m.f. of the secondary circuit is $Z_1 I_1$, and since the secondary is short circuited, it is

$$Z (I_1 + I \cos \omega) + Z_1 I_1 - a x I \sin \omega = 0$$

These are the two fundamental equations of the repulsion motor:

Primary circuit:

$$e_0 = Z (I + I_1 \cos \omega) + I Z_0$$

Secondary circuit:

$$0 = -a x I \sin \omega + Z (I_1 + I \cos \omega) + Z_1 I_1 \quad (5)$$

Where we assumed the impressed e.m.f. e_0 as zero vector

From the second equation it follows:

$$I_1 = \frac{-I (Z \cos \omega - a x \sin \omega)}{Z + Z_1}$$

Substituting this in the first equation, gives:

Primary current;

$$I = \frac{e_0}{Z} \frac{Z + Z_1}{a x \sin \omega \cos \omega + Z \sin^2 \omega + Z_0 + Z_1 + \frac{Z_0 Z_1}{Z}} = e_0 (a_1 + j a_2) \quad (6)$$

Secondary current;

$$I_1 = \frac{e_0}{Z} \frac{Z \cos \omega - a x \sin \omega}{a x \sin \omega \cos \omega + Z \sin^2 \omega + Z_0 + Z_1 + \frac{Z_0 Z_1}{Z}} = e_0 (b_1 + j b_2)$$

Hence,

$$\text{Power-factor: } \cos \phi = \frac{a_1}{\sqrt{a_1^2 + a_2^2}}$$

$$\text{Volt-ampere input; } Q_0 = e_0 I = e_0^2 \sqrt{a_1^2 + a_2^2}$$

$$\text{Power input; } P_0 = /e_0, I/^\wedge = e_0^2 a_1$$

$$\begin{aligned} \text{Power output; } P &= /E_1, I_1/^\wedge = /a x I \sin \omega, I_1/^\wedge \\ &= a x \sin \omega /I, I_1/^\wedge \\ &= a x e_0^2 \sin \omega (a_1 b_1 + a_2 b_2) \end{aligned}$$

Torque; $T = (P/a) = x \sin \omega / I, I_1/1$
 $= x e_0^2 \sin \omega (a_1 b_1 + a_2 b_2)$

Efficiency; $\eta = \frac{P}{P_0} = \frac{a x \sin \omega (a_1 b_1 + a_2 b_2)}{a_1}$

etc.

Substituting

$Z_0 + Z_1 = Z^1 = r^1 - j x^1$ = total internal self-inductive impedance. Neglecting minor terms, it is, approximately:

Primary current;

$$I = \frac{e_0}{(a x \sin \omega \cos \omega + r^1) - j (x \sin^2 \omega + x^1)} \quad (7)$$

Secondary current;

$$I_1 = - \frac{e_0 (\cos \omega - j a \sin \omega)}{(a x \sin \omega \cos \omega + r^1) - j (x \sin^2 \omega + x^1)} \quad (8)$$

Angle of lag; $\tan \phi = \frac{x \sin^2 \omega + x^1}{a x \sin \omega \cos \omega + r^1} \quad (9)$

Torque; $T = \frac{e_0^2 x \sin \omega \cos \omega}{(a x \sin \omega \cos \omega + r^1)^2 + (x \sin^2 \omega + x^1)^2} \quad (10)$

The secondary current leads the primary current by angle

$$\tan x_1 = a \tan \omega$$

The secondary current comes in phase with the primary impressed e.m.f. e_0 ,
 if

$$\frac{a \sin \omega}{\cos \omega} = \frac{x \sin^2 \omega + x^1}{a x \sin \omega \cos \omega + r^1}$$

hence,

$$a = - \frac{r^1}{2 x \sin \omega \cos \omega} + \sqrt{\frac{x^1}{x \sin^2 \omega} + \frac{(r^1)^2}{4 x^2 \sin^2 \omega \cos^2 \omega}}$$

Above this speed, the secondary current leads the primary impressed e.m.f. e_0 , hence magnetizes.

At $a = 1$, that is, at synchronism, the secondary current equals the primary current, $I_1 = I$, but leads by the angle of brush-shift ω .

At infinite speed, $a = \infty$.

$$I = 0$$

That is: the primary current decreases with increasing speed, down to zero at infinite speed. (In the ordinary induction motor the current can never fall below a certain minimum value, the exciting current).

In this case,

$$I_1 = j \frac{e_0}{x \cos \omega}$$

that is, lags 90° behind the primary impressed e.m.f., hence is 90° ahead of the phase of a transformer secondary current, and supplies the magnetizing current of the magnetic circuit, just as a condenser in the secondary circuit of a transformer would do.

At standstill:

$$a = 0;$$

$$I = \frac{e_0}{r^1 - j(x \sin^2 \omega + x^1)}$$

$$I_1 = \frac{e_0 \cos \omega}{r^1 - j(x \sin^2 \omega + x^1)}$$

$$\tan \phi = \frac{x \sin^2 \omega + x^1}{r^1}$$

$$T = \frac{e_0^2 x \sin \omega \cos \omega}{(r^1)^2 + (x \sin^2 \omega + x^1)^2}$$

Current and torque are a maximum, the power-factor a minimum at standstill.

Backward rotation:

For negative values of speed a the torque T is still positive, hence opposed to the rotation, and the repulsion motor with reversed brush-angle ω acts as brake.

The primary current,

$$I = \frac{e_0}{(a x \sin \omega \cos \omega + r^1) - j(x \sin^2 \omega + x^1)}$$

for negative values of speed a becomes wattless, when

$$a x \sin \omega \cos \omega + r^1 = 0$$

or

$$a = -\frac{r^1}{x \sin \omega \cos \omega}$$

For higher negative values of α , or if at a speed greater than $\alpha = (r^2/x \sin \omega \cos \omega)$ (a very low speed), the brush-angle ω is reversed, the energy component of the primary current becomes negative; that is, the motor returns power into the line.

Unlike the plain series motor, which never returns power into the line, the repulsion motor when reversed becomes a generator, consumes mechanical power as brake and returns electric power into the line, even at low speeds. Experiment verifies this feature.

DISCUSSION OF THEORY.

In the preceding outline of the theory of the single-phase alternating-current repulsion motor, the impedances Z , Z_0 , Z_1 , have been assumed as constant.

While this is approximately the case in the ordinary induction motor, it is not the case with the repulsion motor which works over a wide range of magnetic flux densities.

With increasing load and thereby increasing current and decreasing speed, magnetic saturation is approached and causes a decrease of the impedances Z , Z_0 , Z_1 , which has to be taken into consideration in predetermining the characteristic curves of such a motor. Furthermore, the different component magnetic fluxes are affected differently by saturation. The flux M interlinked with the primary coil is approximately constant and therefore affected by saturation only indirectly, while the flux M_1 at right angles to the line of polarization of the secondary coil is approximately proportional to the load and so reaches saturation at high loads, and the impedances become thereby different in the different directions of the magnetic structure.

The m.m.fs. in the preceding have been treated as vector quantities, independent of their distribution around the periphery of the armature. This distribution, however, is different with the different m.m.fs. The m.m.f. causing the effective flux M_1 is due to a zone of the primary winding within the angle $\pm \omega$ from the axis of the secondary coil, hence nearly a concentrated winding, which gives a flat-topped flux distribution, while the flux M_2 in the direction of the axis of the secondary coil is that of a distributed winding or peaked. For the same m.m.f. the effective flux M_1 is therefore greater than the effective flux M_2 . Taking this into consideration, gives the motor somewhat better characteristics than calculated above. Due to the different wave shapes of the fluxes M_1 and M_2 , they are affected differently

by saturation. The flat-topped flux M_1 reaches saturation at a much higher value, but then over the whole range; while the peaked flux M_2 shows the effect of saturation at a lower value but then gradually, by a rounding off of the peak. In the repulsion motor it is, therefore not sufficient merely to consider the resultant m.m.fs. as vectors but their distribution in the air-gap and the effect of saturation must be taken into consideration in the calculation and design of the motor. An exhaustive investigation hereof has been made by my assistant, Mr. M. Milch, and may be communicated at a later date.

The secondary circuit of the motor has been considered as the seat of two e.m.fs. induced respectively by the rotation through flux M_1 and by the alternation of flux M_2 . These e.m.fs., however, have no separate existence. At synchronism, for instance, the magnetic field is an approximately uniformly rotating field and therefore no e.m.f. is induced in the armature conductors except that required to overcome the resistance. The secondary frequency varies with the load and thereby the secondary self-inductive reactance which we assumed as constant in the preceding discussion. This is best taken into consideration by a theory developed by my former assistant, Mr. S. Sugiyama, of Japan. The primary impressed alternating m.m.f. of the current I is resolved into two component m.m.fs. of half intensity, revolving synchronously in opposite directions. If now a = the ratio of speed to synchronism, the two oppositely revolving components of I revolve with regard to the secondary system with the speeds $(1 - a)$ and $(1 + a)$ respectively. The same consideration applies to the secondary m.m.f., I_1 , and in the secondary system we then have induction at two frequencies, $1 - a$ and $1 + a$, of which the former becomes zero at synchronism. That is, at synchronism the secondary current in the armature conductors is of double frequency, similar as in the ordinary single-phase induction motor. At other speeds it is the superposition of two currents of the frequencies $1 - a$ and $1 + a$, respectively. This theory more closely allies the repulsion motor with the ordinary induction motor. Using the same values of secondary impedance, Z_1 , for both components, obviously leads to identically the same equations as given in the preceding.

The complete investigation of the repulsion motor must also take into consideration the current flowing in the armature coil during the moment where the coil is short circuited by the

brushes passing from commutator segment to segment. The m.m.f. of this short-circuit current of commutation is at right angles to the axis of secondary polarization of current, I_1 , hence has the angle of brush-shift $-(90 - \omega)$. A corrective term must therefore be applied, taking this phenomenon into consideration, essentially of the character of a repulsion machine with negative or generator brush-angle of $(90 - \omega)$ and very high effective secondary resistance. This term is very small or negligible at speeds up to a point somewhat beyond synchronism but becomes noticeable at speeds considerably above synchronism, due to the decrease of the main current at these speeds. The main effect of this phenomenon is that the power-factor of the motor instead of increasing indefinitely with the speed up to 100 per cent at some very high speed (and then decreasing again slightly, with leading current), reaches a maximum somewhere between 90 and 97 per cent., according to the constants of the motor, and then very slightly decreases with increasing speed as is shown in the curve of the power-factor of a repulsion motor in Fig. 2.

DISCUSSION OF STEINMETZ AND SLICHTER PAPERS.

B. G. LAMME:—In the paper presented before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, in September, 1902, the speaker called attention to the fact that there were but two types of single-phase alternating-current motors having suitable characteristics for railway service; viz., that called the "Series Type," and the "Repulsion Type." Both of these motors have armatures like direct-current motors with commutators and brush holders. Attention was called to the fact that both motors have suitable characteristics for railway service, as both automatically give variable-speed characteristics with changes in load. That paper primarily described a single-phase railway system, and the motor formed but an element in the general system. It was a very general opinion at that time that the success of the commutator type of motor for large sizes was doubtful, and the sparking feature was considered a fundamental source of trouble. It was generally conceded that if a motor with series characteristics could be made to operate successfully, it would be a great step in advance in the railway field.

Since that time single-phase railway systems have been more fully developed. Practically, no departures from the general system then indicated have been furnished, and the types of motors developed have been along the lines of the two motors indicated in that paper.

Up to the present time the only suitable motors suggested for this work have been of the commutator type, and have been those having series characteristics. The speaker has suggested that all these motors can be considered broadly under the one class of series motors, as they all have the series characteristics of the direct-current series motor. The speaker further suggested that they be sub-divided into the "Straight-Series" type and the "Transformer-Series" type. The transformer-series could also be arranged in two classes; viz., one in which the armature or field is supplied by an external transformer, and one in which the transformer is placed in the motor itself; this latter is the repulsion type of motor.

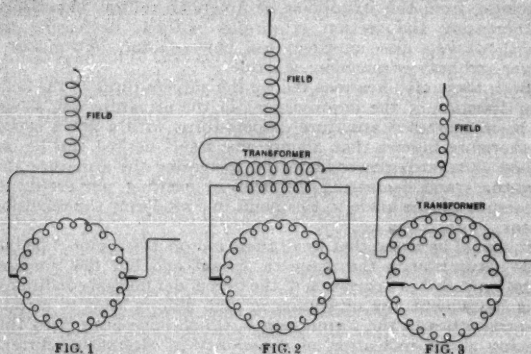
Figs. 1, 2, and 3 illustrate the three classes. Fig. 1 being the straight-series, Fig. 2 the transformer-series and Fig. 3 the repulsion motor. Fig. 2 would be considered as a true series motor, although the armature and field are not directly in series, yet most of the characteristics described as belonging in the repulsion motor apply directly to the transformer motor shown in the figure. Comparing the relations of these motors, viz., the straight-series and the repulsion motor, we will first take up the straight-series.

In this motor, if properly designed, two pressures can be considered; viz., that across the field circuit, and that across the armature circuit. The armature pressure can be made practically non-inductive so that the input of the armature will represent practically true energy. The pressure across the field

is practically at right angles to the armature pressure, and represents very closely the wattless component supplied by the motor. The resultant of these two pressures will then be the line pressure. The power-factor of the motor when running is represented practically by the pressure across the armature winding, increased slightly by the losses in the field-core and winding. Therefore, for high power-factors it is important that the pressure across the armature circuit be made as high as possible, relatively to the applied pressure, and that across the field as low as possible.

There are three ways in which to increase the pressure across the armature; viz., by increase in speed, by increase in the number of wires in series on the armature, and by increase in flux through the armature.

By increase in speed and increase of the wires in series, the armature pressure will be increased without affecting the field



pressure, and therefore the ratio of the armature pressure to the line pressure is increased. Increasing the flux in the armature also increases the flux in the magnetizing-coil in the field, and the pressures of both are increased. Therefore this increase does not improve the power-factor of the machine.

Instead of increasing the armature pressure, the pressure across the field winding may be decreased; this can be done in two ways; viz., by reducing the turns in the field coil, or by reducing flux through the coil. Reducing the flux through the field reduces the flux in the armature winding also, and therefore represents no gain; reduction in field-turns, therefore, is the feasible means of reducing the field pressure. Reduction in field-turns can be accomplished in two ways; viz., by decreasing the effective length of air-gap in the motor, and by increasing the cross-section of gap. By making the gap very small the pres-

sure across the field could be made very small compared with the line pressure, and extremely high power-factors could be obtained, whether the motor is of the straight-series or the repulsion type. Also by increasing the section of the air-gap the turns of the field can be decreased with a given total flux through the coil, and the power-factor can thus be very considerably increased. The first method, viz., decrease in gap, is limited by practical conditions which have been determined from long experience with direct-current work. It should be borne in mind when published descriptions of such motors are given, that the results, as regards power-factor, generally depend upon data which is not given in the description; such as the magnetic dimensions of the armature and field, the length of gap, etc. Therefore, a machine may be described as showing an extremely high power-factor, which may in practice not be a commercial machine, from the standpoint of American railway experience.

Increasing the section of air-gap without decreasing the length of gap also improves the power-factor, but makes a larger and heavier machine, as a rule.

Both these modifications reduce the ampere-turns in the field. The direction of the improvement in the armature was shown to be in increased armature ampere-turns with a given speed. It therefore follows that almost any result desired can be obtained as regards power-factor by increasing the armature ampere-turns and decreasing the field, or exciting ampere-turns. Reference will be made to this point in considering the repulsion motor.

It should be noted that in all these motors there should be but little saturation in the magnetic circuit and but few ampere-turns expended in saturation of the iron under normal conditions. This consequent low saturation in such motors leads to certain characteristics in the torque curves which have been cited this evening as an indication of superiority of alternating-current motors over direct-current motors; namely, a torque increasing approximately as the square of the current. In fact, this superiority of torque should be charged to the low flux-density of the motor rather than to the alternating current. If direct-current motors were worked normally at as low density as the alternating-current motor, then the direct-current motor would show better torque characteristics, and would be comparable with the alternating-current motor. This claim for a better torque in the alternating-current motor compared with the direct-current motor seems to be making a virtue of a necessity.

It is evident from what has been said that the power-factor of the straight-series motor can be made anything desired, it being a question of proportion between armature and field, length of air-gap, amount of material used, etc. In practice a compromise would naturally be made among the various characteristics, and a slight reduction in power-factor is probably of less importance than a corresponding reduction in size and weight. Also large

clearance is probably of more importance than an extremely high power-factor at normal load. In practice it will be found that the armatures of such motors have a large number of ampere-turns compared with the fields, in order to obtain comparatively high power-factors with large air-gaps. The number of poles need not be made such that the product of the poles by the normal speed represents the frequency of the supply circuit; good series motors can be made, and have been made, in which the number of poles were very much larger or much smaller than represented by this relation.

Taking up next the transformer type of motors—Fig. 2; the field is in series with the primary of the transformer, the secondary of which is connected to the terminals of the motor. I would call this a true series motor, although it is not a straight-series motor. In this motor the pressure across the armature can be made practically non-inductive and the pressure across the primary of the transformer will be practically non-inductive. The voltage across the field winding will have practically 90° phase relation to that across the primary of the transformer, and the magnetic field, set up by the field winding, will have a 90° relation in time to the magnetic field in the transformer, as in the repulsion motor. In this motor the voltage across the transformer will be highest at light loads and will decrease with load until zero speed is reached. At start there is lowest flux in the transformer and highest flux in the field winding. Such a motor will have speed-torque characteristics very similar to those of a straight-series motor, except as affected by the actions taking place in the transformer itself. If the transformer possesses no reactance, then at start the current in the armature should be the same as if connected as straight-series motor, and the conditions of torque at start should be the same. If the transformer has reactance, then at start the current in the armature will not be quite equal to the current which the armature will receive if coupled as a straight-series motor, assuming the transformer to have a 1 to 1 ratio. Neither will the armature current be exactly in phase with the field current; therefore the starting torque of a motor connected in this way will be slightly less than the torque of the same motor if connected in straight-series. This is on the assumption that the transformer is one proportioned for small reactance; but if the primary and secondary windings of the transformer should be on separate cores with air-gap between, then the reactances of the windings are considerably greater than in the above case. Therefore, we should expect a motor with such a transformer to give still lower torque than the straight-series with the same current supplied from the line.

In a repulsion motor the transformer is combined with the motor itself and the primary and secondary windings are upon different cores with an air-gap between. The starting conditions of such a motor as indicated above should be poorer than

the straight-series motor, or for the same starting torque somewhat greater apparent energy should be required. It stands to reason that applying the current directly to the armature winding should give greater ampere-turns and better phase relations than generating this current in a secondary circuit, and not under ideal transformer conditions. The tests which have been made, as well as the results shown in the curves of the papers given to-night indicate this. It is to be noted that the torque curve is not the same shape near the zero speed point as the torque curve of the series motor.

Series motors and repulsion motors may be indicated in the simple form shown in Figs. 4 and 5. In the diagrams of the repulsion motor (Fig. 5), two field-poles, *FF*, are shown, and two transformer-poles, *TT*. To obtain high power-factors on such a motor the ampere-turns in *T* must be very much greater than in *F*; which means that the ampere-turns in the secondary or arma-

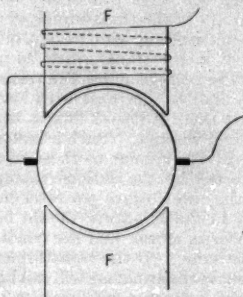


FIG. 4

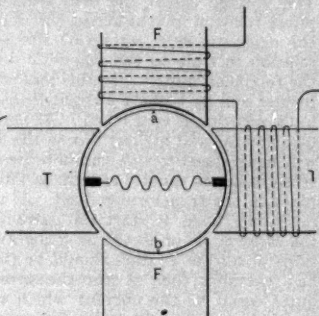


FIG. 5

ture are much greater than in the exciting field, as in the series motor. The high power-factor obtained with these motors is therefore due principally to the small ampere-turns in the field and the small pressure across the field.

For instance, with brushes set at an angle of 16° , from the primary or resultant field, the ratio of armature to exciting field-turns would be almost 5 to 1, a ratio which will also permit of extremely high power-factors in well-designed straight-series motors over wide ranges of speed. To this feature should be credited the good power-factors claimed for the repulsion motor. In either the series or repulsion type of motors, high power-factors, especially at low speeds, are directly dependent upon this fact of high ratio of armature to field, and with a high ratio high power-factors should be obtained without crediting the result to leading currents in the armature. In the diagram of the repul-

sion motor, the line current indicated flows through both the field winding and the transformer winding. The primary current sets up a magnetic field in the exciting windings in phase with the line current. If it also set up a field in the transformer in phase with the line current, then the electromotive force generated in the armature winding due to rotation would have a 90° relation to the electromotive force set up by the transformer, and a correcting or magnetizing current would flow. This flow is in such direction that it corrects the relation between the two pressures in the armature by shifting the transformer magnetism one-quarter phase later than the exciting field magnetism. This armature corrective current may thus be considered as magnetizing the transformer, making the primary input to the transformer practically non-inductive; but this magnetizing or correcting current may be considered as flowing in a circuit at right angles to the field magnetic circuit, and having practically no effect on the field circuit. Therefore as a rough approximation, the exciting field may be considered to represent the wattless component of the input, and the transformer field the energy component, as in the series motor. As to the statement that the magnetizing current in the armature reduces the wattless component of the exciting field, the speaker does not accept it broadly. If this component is reduced, then another component of practically equal value is introduced somewhere else, for the power-factors obtained with such motors can be accounted for by the high ampere-turns in the armature winding, compared with the field or exciting ampere-turns. If the armature current improves the power-factor by diminishing the magnetizing or exciting field, then the curves in Figs. 1 and 4 of Mr. Slichter's paper should show it. The speaker has gone over both sets of curves calculating the wattless components from the power-factors. From this and other data in these curves, he finds that beginning near synchronous speed the wattless component in the motor goes up slightly faster than would be represented by the field excitation, assuming it to be entirely wattless. Therefore, according to these curves, the power-factors at lower speeds are not quite as good as would be obtained by a field entirely inductive and the armature entirely non-inductive, in a straight series motor. These calculations are rather approximate, as the curves do not check at all well with each other. For instance, the output of the motor as represented by the input multiplied by the power-factor and by the efficiency, does not check with the output as represented by the product of speed by torque, in either set of curves, the discrepancies being as high as 10 per cent. In Fig. 4, for instance, either the torque or the speed is too high for the lower speeds. Checking back on this curve, using either the speed and torque or the power-factor and efficiency for determining the output, the speaker finds that the wattless component in the motor at 190 revolutions is approximately 20 per cent higher than it would be if the field excitation alone were wattless,

assuming at 440 revolutions the wattless component is represented purely by field excitation; that is, from 440 to 190 revolutions the wattless component is increased 20 per cent over that which would be represented by field excitation alone. This indicates that not only should the field excitation be considered as practically wattless, but that in addition there is a wattless component due to reactances in the armature windings.

The armature current can be split into two components, one of which is partly magnetizing and represents no torque. The other component is in phase with the field magnetism and therefore represents torque. The magnetizing or wattless element may be comparatively small, as the number of turns in the armature is relatively large, but the armature thus carries at times a slightly larger current than the straight-series motor.

A further inspection of the diagram (Fig. 5) indicates how the power-factor of the motor can be made very high at synchronous speed. At all speeds the pressure generated in the armature due to rotation in the field of F , is practically equal to the pressure generated by the transformer T , thus making zero pressure across the terminals. But also at synchronous speed the pressure generated by the exciting field acting as a transformer, between the points $a b$, will be practically equal to the pressure generated in the winding by rotation of the winding in the transformer field. Therefore across $a b$ the pressure is practically zero with these conditions, but the frequency remains the same as that in the field. If now the magnetizing current be supplied across the points $a b$, then the required ampere-turns for magnetizing the motor can be supplied at practically zero pressure, and the turns of the external magnetizing field can be omitted. Therefore, under this condition the wattless component is practically zero and the power-factor becomes practically 100 per cent. This is the method of excitation used on certain European single-phase motors in which high power-factors are claimed for full-load running. But this method of excitation does not improve conditions at start, as the same excitation will be required at stand-still, whether the excitation be supplied to the armature or to the field. Therefore this method of excitation does not help the motor at that condition of load which is the severest on the generating and transmission system. It has the advantage of omitting the field exciting winding, but has the great disadvantage of requiring a double set of brushes on the commutator, with but half the distance between the brushes found in the straight-series or the ordinary repulsion motor. I do not believe that such methods of compensation are of sufficient advantage to overcome the complications attendant upon them.

At zero speed, both the straight-series and the repulsion motors have low power-factors and with equal losses in the motors, the repulsion should have slightly lower power-factor than the series. This question of power-factor at start is largely a question of internal losses in the motor at rest, and the repul-

sion motor in individual cases may show higher than the series motor, because it may be designed with higher internal losses. The real measure of effectiveness is not the power-factor at start, but the apparent input or kilovolt-amperes at start required for a given starting torque. With equally good designs of motors, the speakers' experience is that the kilovolt-amperes will be found to be considerably less with the straight-series than with the repulsion motor, due to the fact that the current is fed directly into the armature and not by transformer action, and therefore the conditions of phase-relation and amount of current in the armature windings are more favorable. Therefore it follows that in order to have the same kilovolt-ampere input for the same starting torque, the repulsion motor should have a smaller length of air-gap than the corresponding straight-series motor, or should have a greater section of air-gap, which means greater weight of motor. This is one of the conditions which has led

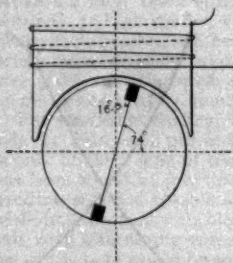


FIG. 6

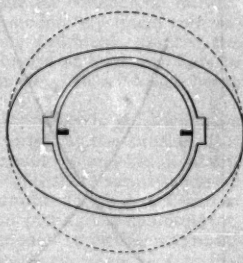
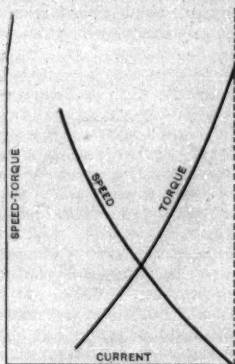


FIG. 7

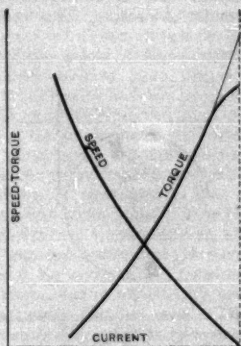
the speaker to the advocacy of the series motor rather than the repulsion motor, as he has considered this condition of starting of more importance than running; although he is satisfied that many of the running conditions of a well-designed series motor will be found in practice to be superior to those of an equally well-designed repulsion motor.

Referring again to Fig. 5, it will be noted that two fields are set up in such a motor, and that at synchronous speed these two fields are equal. In the straight-series motor there is but one field set up, the other being omitted. It is evident that the straight-series motor with the current supplied directly to the brushes can have a smaller section in certain parts of the magnetic circuit than is required for the repulsion motor, and that therefore the weight of material would be less, and the external dimensions can be less. In Fig. 7 the heavy line represents outlines of series and the dotted line those of repulsion motor; therefore, it follows that for equally good designs and same fre-

quency, the straight-series motor should be more compact, and should weigh less than the repulsion motor. It is reasonable to expect this, as the repulsion motor contains a transformer in addition to the other parts found in the straight-series motor. Furthermore, the transformer found in such a motor is one with an air-gap, and with the windings on two separate elements, and therefore cannot be so well proportioned as a separate transformer could be. Also, there is a transformer for each motor, and in a 4-motor railway equipment, for instance, there would be four transformers of smaller size against one larger transformer used with the series motor, this larger transformer having a closed magnetic circuit, and of a highly efficient design compared with the transformers in the motors themselves.



Straight Series Motor



Repulsion Motor

A further point should be taken up in the comparison of these motors; viz., the current in the coil short-circuited by the brushes. This coil is a secondary to the field and the current in it is necessarily greatest at the period of strongest field. Therefore, this current will be greatest at the time of starting. If the repulsion motor and the straight series motor have the same field strength at start, then the short-circuited current should be the same in each. But as the current is fed into the armature in the repulsion motor through transformer action, it will as a rule be found that the starting field strength of such a motor is slightly greater and the starting armature strength slightly less for a given torque than is found in the straight-series motor having same ratio of armature to field windings. Therefore the short-circuit current at start will be somewhat larger for the repulsion motor than for the corresponding straight-series motor.

This short-circuit current may be somewhat less near full speed than in the straight-series motor, but it is not the full-speed condition which is the serious one. The short-circuit current at start is one of the most serious conditions which confronts us in alternating-current motors, and is also of great importance where there is any considerable operation on low speeds. The speaker advocates a type which he considers gives the easiest condition in this regard. This short-circuiting cannot be entirely avoided in any of the motors brought out without adopting abnormal and questionable constructions, although devices like narrow brushes, sandwich windings, etc., have been proposed. In certain foreign motors the brushes used are so narrow that they cover practically the width of one commutator-bar. As such motors are generally built with a very large number of bars, the brushes used are extremely narrow, being approximately 0.2 inch thick at the tip. This will undoubtedly lessen the short-circuiting, but simply transfers trouble to another point; a brush 0.2 inch thick is not practicable for commercial railway service; at high speeds, with only a moderately rough commutator, such brushes will be liable to chip and break; further, the brush on a street-car motor should bridge at least two bars to give good, smooth, brush operation; in practice, a 0.5 inch brush on motors of 100 h-p. should be used.

The sandwich winding, which consists of two or more windings side by side, will prevent short-circuiting at the brushes, but is only another way of transferring trouble to another point; it has been found in practice that it is difficult to run a sandwich winding without trouble at the commutator with direct current without a tendency to blackening and pitting the commutator, and with alternating current this tendency to pitting and burning of the bars would be equally great.

As a rule, there is little difference between the operation of repulsion and straight-series motors as regards sparking, except that the repulsion motors generally have greater current in the short-circuited coil near zero speed, and therefore show greater tendency to heat and spark. At or near synchronous speed, there appears to be very little difference in the commutation, although the speaker has never given the repulsion motor the same test of long-continued service as he has in the case of the series motor. These series motors have never shown any tendency to give trouble on the commutator, and on an exhibition car equipped with four 100-h-p. motors, the commutators have never been sandpapered since the equipment has been put into service. This exhibition car is used principally for showing the accelerating properties of the motors; therefore, the speaker does not hesitate to say that the commutation of the straight-series motor will prove to be equal to that of the direct-current motor. Wide brushes are used with it, such as have been used in street-railway motors.

It is well known that with large direct-current motors, espe-

cially when operated at very high speeds, there is a tendency to flash across the commutator, or to the frame of the motor, if the field circuit be opened for a period long enough to allow magnetism to drop to zero, and then the field be closed again. In this case there is a rush of current before the field has had time to build up, and this rush of current, together with field distortion, may cause serious flashing. In the alternating-current motor, whether of the straight-series or the repulsion type, this tendency should be entirely absent. In the straight-series motor the magnetism falls to zero once in each alternation, and therefore if this tendency existed, flashing would occur continuously. Furthermore, a properly designed straight-series motor can be short-circuited across the brushes without injury to the motor, and can continue to operate in this way; therefore, if the machine can be short-circuited in this way, there is evidently no tendency to maintain an arc.

Returning to the subject of power-factors it should be noted that high power-factors are very frequently found in motors of low or only moderately good efficiency. This low efficiency to a slight extent explains the high power-factor in some motors, both polyphase and single-phase. Low efficiency means higher true energy expended, and with a given wattless component it means higher power-factor. It is the old problem of increasing the power-factor by wasting energy in a circuit instead of reducing the wattless component. The power-factor of any alternating-current motor can be very considerably increased by putting resistance in series with it. Instead of this resistance the internal losses of the motor may be made higher, which will accomplish the same results. The motor will therefore appear to have a higher power-factor than it really deserves, if efficiency of the motor is taken into account. If, for instance, the efficiency at 300 rev. shown in Mr. Slichter's Fig. 4 would be made as high as on direct-current motors, then the power-factors with the same magnetizing and other conditions, would have been approximately four per cent lower. This lower power-factor would not have made any harder condition on the supply circuit, but actually would have made a somewhat easier condition, as the supply system would have furnished about eight per cent less kilovolt-amperes. For lower speeds this difference in power-factor will be greater, and less for higher speeds. A high power-factor at start, obtained by the use of resistance in series with the motor by high internal losses which do not represent torque, is therefore a detrimental condition rather than a good one, as it means increased kilovolt-ampere expenditure for a given torque. This is merely given as an illustration showing that power-factor in itself is not a true indication of conditions, but must be accompanied by other data; this is not a criticism of these motors, but is a general condition, found to a greater or less extent in all alternating-current motors.

In conclusion the speaker wishes to ask a few questions in regard to some of the points brought out in these papers. One point in connection with Fig. 1, Mr. Slichter's paper, is the high power-factor of 50 per cent shown at start. The speaker would like to know how this power-factor can be so high when the motor is doing no work at this point. Is this power-factor due to high internal losses of the motor, or is an external resistance added? The speaker has tested a number of series and repulsion motors, and for motors of this capacity, as a rule, the power-factors have been somewhat lower than this; the losses in the repulsion motor for a given starting torque are always greater than in the straight-series motor, but the volt-ampere input for the same torque was also greater so that the power-factors in some cases were very nearly equal.

Also, Mr. Slichter states that the motor shown in Fig. 4 is for constant-speed running; does this mean running at a practically steady load, or is this motor intended for constant-speed work, in the sense of a shunt-wound direct-current motor?

In the comparison with the direct-current motor it is stated that the alternating-current motor remains on the controller for 16 seconds, and the direct-current motor for 25. Would it not be true that the direct-current motor could remain on the controller for a shorter time, if designed with an unsaturated field, as the alternating-current motor? Is not this a property of an unsaturated motor, rather than an alternating-current motor?

A. S. McALLISTER:—In the papers presented this evening, mention is made of the fact that the repulsion motor, when driven against its torque, acts as a generator; and when the negative speed becomes of a value such that its product with the torque exceeds the internal losses of the motor, the machine will feed energy back to the line. The analytical equations given in Mr. Steinmetz's paper furnish an explanation of the cause for this action on the part of the machine. These equations may be represented graphically by a simple diagram, and it is believed that the diagram affords a readier interpretation than do the equations.

When the rotor of the repulsion motor is stationary, measuring instruments placed in the primary circuit will indicate an apparent impedance, having power and reaction components. The power component, which will here be termed "resistance," represents the resistance effect of the primary coil, the equivalent resistance effect of the secondary circuit, and the effect of the core loss at starting. In the impedance electromotive force for one ampere—diagram of Fig. 1—this resistance, R , is represented by the line AB , while the line BC shows the apparent reactance, X , and the cosine of the angle CAB gives the power-factor of the motor at starting. When the motor operates at a speed, S , the power component of the apparent motor impedance—volts for one ampere—is increased by a certain value PS , CD in the diagram, P being a coefficient depending upon the relative

strength of the field which causes the generation of electromotive force in the armature conductors at speed S , and hence depends upon the position of the brushes. If the apparent reactance of the coils remained of value X at all speeds, then at speed S the apparent impedance of the motor becomes :

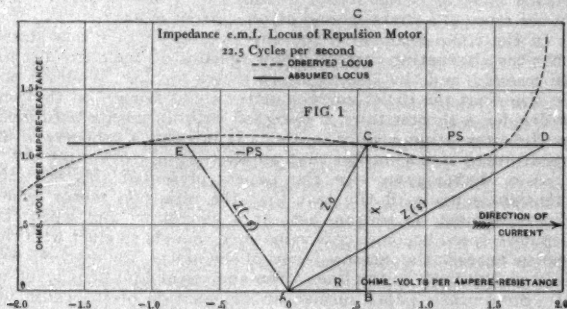
$$Z_s = \sqrt{(R+PS)^2 + X^2}$$

and for impressed electromotive force of E the current will be

$$I = \frac{E}{\sqrt{(R+PS)^2 + X^2}},$$

and the power-factor, $\cos \theta$, is

$$\cos DAB = \frac{R+PS}{\sqrt{(R+PS)^2 + X^2}}$$



The power input is

$$E I \cos \theta = \frac{E^2 (R+PS)}{(R+PS)^2 + X^2}$$

If, independent of the change in speed of the rotor and variation of the relative values of the primary and secondary currents, the total internal losses of the motor be considered proportional to the square of the primary current, the output would be

$$I E \cos \theta - I^2 R = \frac{E^2 PS}{(R+PS)^2 + X^2}$$

and, the ratio of output to speed, the torque will be

$$I^2 P$$

The discrepancies between the assumptions made and the physical facts involved will be evident from a study of the formation of the above equations. It will be observed that the equations here given will become identical with the approximate equations of Mr. Steinmetz if for each value used above there be substituted its equivalent as given below,

$$R = r^1$$

$$X = X \sin^2 \omega + X^1$$

$$P = X \sin \omega \cos \omega$$

$$S = a$$

An inspection of Fig. 1, or of the equations above, will reveal the fact that when S is negative and of a value such that $-PS =$

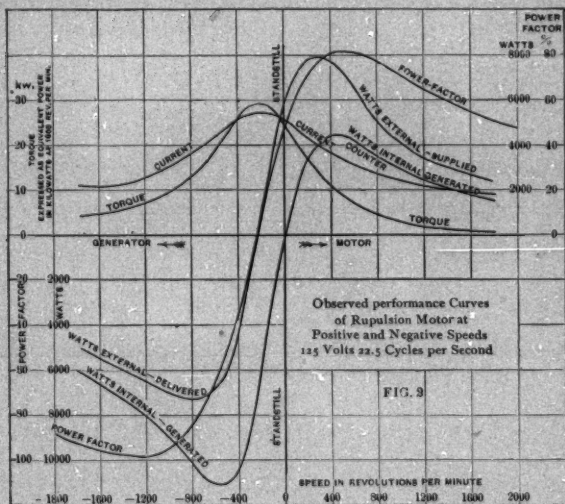
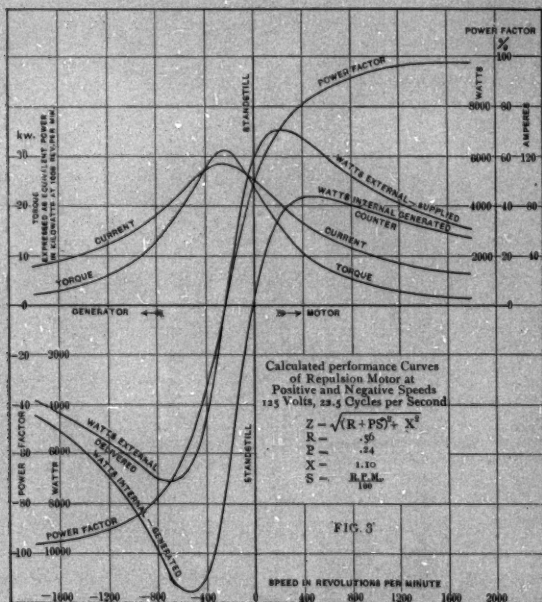


FIG. 2

R , the apparent impedance of the motor becomes X ; the current is E/X and represents no energy flowing either to or from the motor; that is, the machine is operating as a generator and supplying its own losses. A further increase of negative speed causes the power component of the apparent motor impedance to take on a negative value; the power-factor becomes negative indicating that energy is flowing from the machine.

The curves of Fig. 2 show the results of tests of a certain repulsion motor while those of Fig. 3 give the calculated performance of the same motor, proper substitution having been made in the equations above.

In the discussion of the theory of the repulsion motor, Mr. Steinmetz states that the effect of the short-circuit by the brush of active coils tends to a reduction of the power-factor at high speeds; which statement may be taken as an explanation of the fact that the power-factor observed in case of high speeds is much below that calculated, as will be seen from a comparison of Figs. 2 and 3.



The neglect of the counter-torque, due to the local current flowing in the coils under the brushes, leads also to error in assuming that the repulsion motor tends to increase indefinitely the speed of its rotor as the applied electromotive force is increased or the load decreased, since in reality experiments show that the rotor tends to reach a certain speed above which, if it be driven mechanically, it acts as a brake.

PRESIDENT ARNOLD:—Since this discussion may properly be divided and naturally divides itself into two parts, such as motor designing and the application of single-phase alternating-current

motors to railway work, it would be proper at the present time to give Mr. Steinmetz an opportunity to answer Mr. Lamme's questions and any of the other questions which have been asked.

C. P. STEINMETZ:—An alternating-current series motor, to have a reasonably good power-factor, must have a high ratio of armature magnetomotive force to field magnetomotive force; this conclusion, reached ten years ago by Mr. Eickemeyer and the speaker, is agreed to by Mr. Lamme; but there is a limit to the indefinite increase of this ratio, for the reason that the armature circuit is not really non-inductive, and there comes a point when the increase in the armature self-inductance is greater than the decrease in the field self-inductance. For the motor on which experiments were made ten years ago, this ratio was between 3.5 and 4, but very high frequencies were then used; with lower frequencies the ratio can be increased, yet there is still a limit to its indefinite increase. The fact of self-inductance in the armature explains the reason that the power-factor, calculated as Mr. Lamme calculates it—on the assumption of a non-inductive armature—gives higher values than tests show. Moreover, a brush shift of 16° is not equivalent to a ratio of 1 to 5. The two sections of the winding must be combined approximately vectorially, giving a ratio of $\sin 16^\circ$ to $\sin 74^\circ$, or about 1 to 2.86, and this ratio will correspond to a lower power-factor than that obtained for a ratio of one to five.

One great advantage of the modern repulsion motor is that it uses a pole-arc of 180° , or the largest section of air-gap possible, and so secures at low speeds so high a power-factor that it is not necessary to go to speeds far above synchronism. The result thereof is a small number of poles, great number of commutator segments per pole, hence small short-circuit current in starting and running, and a low-speed commutator.

The repulsion motor has inherently such a high power-factor that a large air-gap and a high flux-density may be used, hence with heavy currents, magnetic saturation is approached or passed in part of the magnetic structure, and a bend occurs in the torque curve. It is not feasible to use flux-densities quite as great as in the direct-current series motor. Further, at low speeds a point must be reached where the electromotive force of rotation becomes small compared with the electromotive force of self-induction, however small the latter may be, and below this speed the torque and current do not increase, but remain constant both in the repulsion and in the series motor.

There is no doubt that a motor designed as a series motor will give larger output and greater efficiency than the same motor used as a repulsion motor, as Mr. Lamme states; but, on the other hand, a motor designed to be repulsion motor and then run as a series motor will give the opposite result—that is, the output will be greater and the efficiency better, when operated as a repulsion motor. The reason for this is simple, and is found in the fact that a series motor must have definite polar projections,

whereas the repulsion motor uses a distributed winding, similar to that of an ordinary induction motor; hence, a low inductance is obtained with a correspondingly high power-factor. Thus the transformer feature of the repulsion motor requires a change in design, and makes a comparison of the relative performance of a particular design first, as a repulsion, and then as a series motor, meaningless.

P. M. LINCOLN:—The observations made on a car of about 40 tons, equipped with four 125-h-p. alternating-current series motors, show that when in motion at speeds not above four or five miles an hour, the motor sends power back into the line on reversal as indicated by a wattmeter; the wattmeter reverses when the fields are reversed and current is on. The same characteristic has also been reproduced in shop tests, where a straight-series motor has been used as a generator to feed power back into the shop circuit to which it is connected, by driving it suitably by another motor. Another characteristic of the alternating-current series motor is that it will always build up as a direct-current generator when the reverse switch is thrown and no power applied; it acts just the same as the direct-current series motors and can be used in the well-known way as an emergency brake. In fact on one occasion, when the air brakes failed, when the car was running at high speed, this emergency brake was thrown and the car stopped very promptly, just as it would with a direct-current motor.

On page 66, referring to the speed-time curves, Mr. Slichter gives the comparative inputs for alternating and direct current, for the same car running the same distance, as 0.72 kilowatt-hours for the direct and 0.685 for the alternating current, approximately for the alternating current five per cent less energy; but the rheostatic loss for the direct-current curve amounts to approximately 15 per cent of the total curve area. He accounts for the difference of five per cent, whereas the curve areas seem to indicate that there should be a difference of at least 15 per cent, since the alternating current motor does not include the rheostatic losses.

MR. SLICHTER:—The fact that the power-factor at starting, shown in the first curve, is as high as 50 per cent, is due to the large losses and low efficiency of this particular motor. This motor was designed some time ago, when the matter of commutation was considered to be very serious, and radical precautions were taken to prevent bad sparking at the expense of efficiency. Recent experience has shown that these precautions are not necessary and as a result it has been possible to improve the efficiency.

This low efficiency, 80 per cent, is also the cause of the small difference between the energy consumption of the alternating-current motor and the direct-current motor as the length of run increases. The low efficiency of this motor at high speeds counterbalances the saving effected by potential control during

acceleration. With a later design of alternating-current motor this efficiency would be much higher and the net saving by the use of potential control would be much more noticeable.

Referring to the motor of Fig. 4, it is intended for hauling heavy trains at constant slow speeds with few stops; in other words, long-distance freight haulage.

The fact that the controller of the alternating-current motor is cut out in so short a time, 16 seconds as against 25 for the direct-current motor, is due to the steep speed characteristic of the motor.

In reply to Mr. Lamme's criticism of the curves, they are intended to give a general view of the characteristics of the repulsion motor and are for this purpose extended over values of current outside the working range of the motor? In this range of the curves there are several points of curvature which are difficult to check exactly, since only a few points were plotted to show the general direction.

RALPH D. MERSON:—Mr. Slichter speaks of voltage control; what method of voltage control was used on these motors, was it such as would be used commercially? What were the comparative weights of alternating-current motors, and direct-current motors, for the same work and for approximately the same performance, either on the basis of efficiency of the motor itself or the total efficiency of acceleration? What were the relative weights of the motor and of the complete car equipment, for alternating current and direct current? Also what pressure would he use with the alternating-current motor? Mr. Slichter says these motors can be wound for high-pressure; how high? and what method of control would be used in that case? Another important point is, can the repulsion motor be so designed as to be a good repulsion motor, and yet be a pretty good direct-current motor?

It will be quite difficult to get the people responsible for existing large direct-current railway systems up to the point of changing over any considerable portion of the road at one time. The change can be much more easily accomplished if it can be made more or less gradually as, for instance, by changing outlying sections first, and this can be done if the motor is such as can be used on both the direct-current lines and alternating-current lines. As a matter of interest, what was the number of poles of the motors represented by these curves?

A. H. ARMSTRONG:—The curves given on the first three pages of Mr. Slichter's paper refer to four-pole motors and the curves in Fig. 4 to a six-pole motor, all operating at 25 cycles. Mr. Mershon stated the matter about right when he asked if a repulsion motor could be designed to operate well on alternating current and at the same time be operative on direct current. It is not possible to get equally good results both alternating current and direct current, but a good alternating-current motor will give sufficiently good results when operated on direct current to enable a car so equipped to operate over direct-current lines.

The repulsion motor can be wound for 2000 or 3000 volts direct, without the use of transformers; but experience in operating with such pressures on railway equipments is yet to be had, and it is not known how much deterioration will be produced by the constant jarring and crystallizing of the insulation. Should it become too expensive to maintain high-pressure motor winding, it will be necessary to resort to the use of transformers; with the high-pressure motors, control will be effected by either a compensator or by the insertion of resistance, as in the present direct-current control.

If a car stops once in five miles, the small difference in efficiency in starting between rheostatic and pressure control would have practically no effect upon the general efficiency of the system as a whole. Again of one or two percent in the average car energy would not compensate for the additional complication. It will be entirely feasible to consider 2000 or 3000 volts on the field of the repulsion motor without any intervening apparatus, but this, as stated before, will be largely determined by commercial operation. The repulsion motor having no metallic connection between field and armature, and thus not being in any way limited by commutation can have its field wound for as high-pressure as operating conditions will permit.

No definite figures can be given for the relative weight of alternating-current and direct-current railway motors. The capacity of direct-current motors has been very carefully worked out during the past few years; but the alternating-current motor is not in commercial operation, it has not been possible to obtain experimental data upon its relative capacity and hence its weight and size compared with the direct-current motor must remain an open question for the present. The alternating-current motor will undoubtedly weigh somewhat more than the direct-current motor for the same service performed, but the percentage increase cannot be stated with any degree of accuracy at the present time.

In a high-pressure motor system using trolley pressure directly on the field, the control system should not weigh much more than that required for direct-current motors. If, however, a low-pressure motor is used with the high-pressure trolley, it will require the installation of a step-down transformer, which weight must be considered in addition to the regular control system. The average energy-consumption of some of our suburban cars reaches as high as 75 to 100-kw., and the addition of a 100-kw. transformer of either the oil-cooled or the air-blast type will constitute an appreciable addition to the weight of the car equipment.

PRESIDENT ARNOLD:—The question of the destruction of the insulation or crystallization of the metal used in the construction of high-pressure motors has been pretty thoroughly answered in practice by the use of such high-pressure motors abroad; the line in Italy, using 3000-volt motors, has been operated for two

or three years and no such objection has been used against it. If abroad they can build motors which can run successfully under that pressure, we should be able to do the same.

C. P. STEINMETZ:—The present alternating-current motor, either series or repulsion type, has a somewhat lower efficiency and is somewhat heavier than the direct-current series motor, but this difference is less than would be expected; the principles involved in the design of the two types are quite different, so that no direct comparison of one with the other can be made.

There is no inherent reason why the efficiency and weight of the alternating-current motor should not be on a par with those of the direct-current motor, after the type has been further developed.

ROBERT LUNDELL:—A possible reason why the efficiency of the alternating-current motor is not as great as that of a direct-current motor is because the hysteresis losses and the eddy currents are bound to be larger in the alternating-current motor. In the alternating-current motor we have to take care of the eddy currents and hysteresis losses in an apparatus which must weigh more much than the armature of the direct-current motor. As the hysteresis or core losses are due to the cycles per second, the density of the magnetism and also to the weight, it seems to me that the weight is bound to be greater in the surrounding frame, that is, the field magnets which surround the armature of the alternating-current motor. Is not that one reason why the efficiency of the alternating-current motor cannot possibly be as high as that of the direct-current motor?

O. S. LYFORD, JR.:—In a direct-current motor, we can get 200 horse-power in a motor on the truck, or 400 horse-power in a pair of wheels on one truck; will Mr. Slichter say whether the 175 horse-power motor described on page 66 is of such dimensions that it could be placed on the ordinary interurban car-truck with 33 or 36 inch wheels? How large an alternating-current motor can we get for a 33 or a 36 inch wheel? In other words, what is our limit at the present time in the motor-car field?

W. I. SLICHTER:—That motor is designed for locomotive work and would not be of dimensions to go under a car having 33 inch wheels.

The ideas on this subject are developing very rapidly; one could not say that a 100 horse-power motor could be placed there, but perhaps it would not be advisable to say that a larger motor could not be.

B. G. LAMME:—The Westinghouse Electric and Manufacturing Company is building 150-h-p. motors which will go in on 33-inch wheels, closely; easily on 36-inch wheels. It has been determined that we can put 200-h-p. motors on 36-inch wheels. That is one limit.

PRESIDENT ARNOLD:—If you gentlemen who build railroads will call for the motors, you will probably get them.

H. A. WAGNER:—Does not the repulsion type of motor take

somewhat more copper in the field than the series motor? and in reversing the former, is it proposed to move the brushes or to feed the current into the stator at a different point?

C. P. STEINMETZ:—The repulsion motor can be reversed by changing the point of entrance of the current to the primary wires, without changing the brushes; thus the primary winding may have current brought to it at several different points in the repulsion motor, and the brushes need not be shifted. The relative amounts of copper in the armature and field may be varied to some extent to suit the design, but there is no essential difference in the proportions of material.

[COMMUNICATED AFTER ADJOURNMENT BY B. G. LAMME.]

In the discussion of the papers of Messrs. Steinmetz and Slichter, the writer indicated in a very general way some of the reasons which led him to the advocacy of the straight-series motor. Some of the more important of these reasons can be classified as follows:

Lighter weight with a given output and given performance.

Larger air-gap with a given input at start.

Less short-circuiting at commutator at start, with a given starting torque.

Ability to operate the motor on various pressures by simply using taps on the transformer which supplies the motors. For instance: a motor can be run at 3000 volts on one part of the line, or at 500 volts on another part by simply feeding the trolley circuit into a different point in the transformer. Also the transformer can be readily stepped-up to a slightly higher pressure, thus allowing a higher normal speed and ability to make up for delays. This general arrangement will be of especial importance in heavy railway work, now represented by steam service.

The motor will be normally wound for low pressures. It has been claimed that the advantage of the alternating-current motor for railway work is that it can be wound for high-pressure, but, on the other hand, it enables us to wind the motor for low-pressure. Taking into account the troubles that are found with direct-current motors at 500 and 600 volts, the writer believes that one of the greatest advantages of the alternating-current motor is that the motor itself can be wound, if desired, for much lower than 500 volts, while a pressure of 2000 or 3000 can be supplied from the trolley. The writer does not believe that a pressure of 3000 should be supplied directly to the motor. This judgment is based partly on European experience with high pressures on railway motors. A motor wound for this pressure will necessarily be heavier than one wound for low-pressure, even if the same type of motor is retained. Therefore, if low-pressure is to be used on the motor with a step-down transformer on the car, then the writer considers that the repulsion type of motor, being naturally heavier than the straight-series, is used at a great disadvantage, as the equipment contains not only transformers in the motors themselves, but also an external transformer.

A further condition, applying to all alternating-current motors, is the fact, already published, that there is an active pressure between turns on the field of motors. This is of considerable importance considering the overload capacity of such motors. In the direct-current motor a short-circuit can occur between two or more field-turns without immediately disabling the motor. In the alternating-current motor a similar short-circuit will disable the motor. Therefore if the alternating-current motor is to meet the same conditions of service as the direct-current motor, it will require much more insulation in its windings than that required in the direct-current motor, and this in turn means that the motor must be either increased in size, or must be wound for lower pressure. The writer therefore believes that whether straight-series or repulsion motors are used, the motor should be wound for a relatively low pressure.

Mr. Steinmetz's suggestion that these conclusions in regard to relative weights of straight-series and repulsion motors were based on the use of series motors operated as repulsion motors, just as his conclusions were based on repulsion motors operated as series motors is incorrect; for these conclusions have been drawn from designs of straight-series and of repulsion motors, each type being proportioned for its own special method of operation; the writer has designed a number of motors of each type, and a repulsion motor of 125 horse-power capacity was constructed for the purpose of investigation.

Mr. Slichter states that the discrepancies in the curves of Figs. 1 and 4, are due probably to the complicated nature of the calculations of these curves; but his paper states that the curves of Fig. No. 1 "are taken from tests on a 60-h-p. 25-cycle, 500-volt motor." If these curves were obtained entirely by calculation, there could be wide discrepancies which might have been overlooked, if the final results were not checked with each other.

Mr. Steinmetz states that one advantage of the repulsion motor over the series motor lies in the fact that the magnetic leakage should be less, due to the distributed windings of the primary; but he overlooks the fact that in a series motor designed for high power-factor, the magnetic leakage of the exciting field-winding can be made extremely low; the leakage of the two motors will be practically equal if the primary fields are wound for equal pressure; if, however, the repulsion motor field is wound for high-pressure, with a comparatively small number of slots, the magnetic leakage will be higher than on the low-pressure motor, and will therefore be higher than on the series motor. Mr. Steinmetz's opinion of straight-series motors may be based on data obtained about ten years ago. There has been considerable improvement in the art since then, and the development of this motor for commercial railway service has undoubtedly led to proportions and forms of construction not contemplated ten years ago.

[COMMUNICATED AFTER ADJOURNMENT BY CHAS. F. SCOTT.]

The papers and their discussion are notable on account of several omissions. The subject under consideration, namely, the single-phase railway motor, brought forth no question as to the practicability of the single-phase system; it elicited no mention of the polyphase railway motor; it led to no questions regarding the matter of commutation of alternating currents.

It must be borne in mind that it is less than a year and a half since the first authoritative announcement of the single-phase railway motor was made. The announcement was the occasion of much surprise and many were sceptical as to the question whether the single-phase motor was practicable or even possible. The practicability of the single-phase motor is now received without question, and it is tacitly accepted that the single-phase motor and the single-phase system are factors of very serious consequence in the immediate extensions of railway work.

At the Buffalo Convention of the INSTITUTE in 1901, a paper was read by Mr. Berg in the discussion of which Mr. Steinmetz and the writer took part. We concurred with the conclusions of the paper that the polyphase motor was not suited for railway work, and that the efforts of European engineers to introduce polyphase motors for railway work was not along lines which would prove a general solution of the railway problem. There were criticisms at that time and subsequently in the technical press setting forth the backwardness of American engineers and indicating the forward steps which were being made in Europe in the introduction of alternating current for railway work. Our contention, however, was not against the alternating current but against the induction motor for railway work. It is notable that since it has been stated that there is an American single-phase motor, European engineers have taken up the development of single-phase apparatus, indicating thereby the shortcomings of the polyphase railway motor. It is significant that the polyphase motor did not come up for consideration in the general discussion of the single-phase motor in connection with the Steinmetz and Slichter papers.

There was some disappointment in connection with a meeting of the INSTITUTE a little over a year ago at which the single-phase series motor was presented, because certain specific data regarding the design of the motor, particularly in connection with its commutation, were not given in connection with the general engineering presentation of the single-phase system. There seemed to be an idea that there was a mysterious something which had been introduced into the motor as a panacea for the evils of alternating-current sparking, which was being withheld. The papers now under discussion do not deal with the particulars of commutation. The general statement that the single-phase motor, whether of the repulsion type or of the straight-series type, does commutate and commutates successfully, was accepted without question and without awaking any apparent curiosity

as to the methods or devices by which it is accomplished. This illustrates how quickly a new thing passes from the category of that which is doubtful and incredible to that in which it is an accepted fact, from which important commercial results are expected to follow as a matter of course.

The present papers and their discussion deal almost entirely with the presentation of one type of single-phase motor and a comparison between it and a second type. The motor, however, is but one feature, although the fundamental one, of the single-phase system. It is the general system which the motor makes possible, as was intimated in the remarks of President Arnold, which is the thing of real consequence. The significant result of the introduction of this motor is not the motor itself, but it is the use of alternating current throughout the whole system; it is the omission of synchronous converter sub-stations with synchronously running apparatus, rendering the present distribution system one which is inefficient, cumbersome, and sensitive in operation; it is the use of high-pressure and the resulting economy in transmission; it is the many advantages found in the construction of controllers for heavy alternating current over those for heavy direct current; it is the advantages which come from pressure control instead of resistance control; it is the readiness with which energy may be returned to the circuit by the alternating-current motor having pressure control (which is not practicable with the direct-current motor having pressure resistance control); it is the lessened concentration of energy in alternating-current circuits in case of short-circuit; it is the safety to the car equipment on account of the non-flashing of alternating-current motors, thus avoiding one of the serious difficulties in direct-current motors on large equipments; it is the freedom from electrolysis, and, in short, it is the superiority shown by the alternating current over the direct current in practically every element from generator shaft to motor shaft, by which the limitations found in the direct-current system are removed and a new field, the bounds of which are not yet determined, is opened in the development of electric railway service. The outcome of the synchronous converter which has been so great a factor in the railway extensions of the past half dozen years has been the suburban and interurban railway. The single-phase motor opens the way to a new system which has in its elements which promise far greater developments than those which followed the introduction of the synchronous converter.

[COMMUNICATED AFTER ADJOURNMENT BY B. A. BEHREND.]

The writer wishes again to illustrate by a few diagrams the close resemblance between the alternating-current series motor with a compensating coil for the cross-ampere turns of the armature on the one hand and the repulsion motor on the other. Fig. 1 shows the straight-series motor; Fig. 2 shows the series motor with compensating-coil. In order to obtain a high power-

factor it is necessary, as has also been pointed out by Mr. Steinmetz and Mr. Lamme, to make the armature magnetomotive force considerably greater than the field. This is indicated in Fig. 2 by showing the field-coil F with few turns and the compensating-coil C with a large number of turns; instead of passing

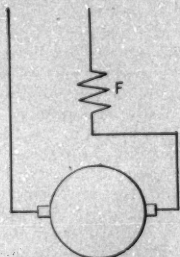


FIG. 1

Straight Series Motor

the field current through the compensating-coil C , this coil can be short-circuited itself as illustrated in Fig. 3. The main current also can be passed through the compensating-coil C in series with the field F and the armature be short-circuited on itself, thus making the armature the secondary and the compensating-coil

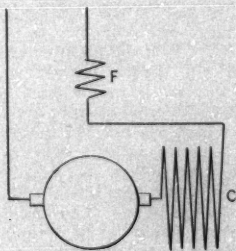


FIG. 2

Series Motor with Compensating
Coil

the primary instead of the reverse, as in Fig. 3. The coils F and C may be replaced by one resultant-coil R , leading to the repulsion motor Fig. 5.

From the above considerations, it follows that, with very close approximation, the torque, power-factor, and the

efficiency of the compensated series motor represented in Figs. 3 and 4 are equal to those of the repulsion motor Fig. 5. There is no reason why the power-factor of the repulsion motor should be better than the power-factor of the compensated series motor

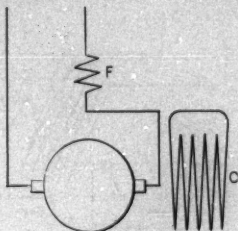


FIG. 3

Series Motor with Armature
as Primary and Compensating Coil
Short-circuited as Secondary

of Fig. 2, and Mr. Steinmetz's Fig. 4 showing the comparison between a repulsion motor and an Eickemeyer compensated series motor is therefore most misleading. If the motors are

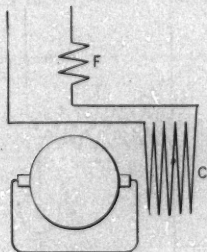


FIG. 4

Series Motor with
Compensating Coil as Primary
and Armature Short-circuited as
Secondary (Repulsion Motor)

designed with the same degree of care they should have approximately equal power-factors at all speeds. Mr. Steinmetz says: "The secondary current of the transformers, however, lags slightly less than 180° behind the primary current; that is, con-

sidering it in the reversed direction, is a leading current with regard to the primary current. The current in the armature in Fig. 3 is therefore a leading current with respect to the line current and so not only does not add an additional lag, but reduces the lag caused by the self-induction of the field exciting-coil."

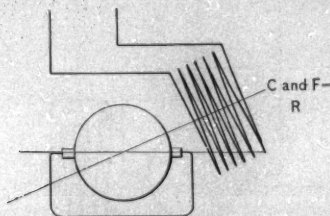


FIG. 5

Repulsion Motor Field and Compensating
Coil Combined

Mr. Lamme says on this point: "In either the series or repulsion type of motors, high power-factors, especially at low speeds, are directly dependent upon this fact of high ratio of armature to field, and with a high ratio, high power-factors should be obtained without crediting the result to leading currents in the

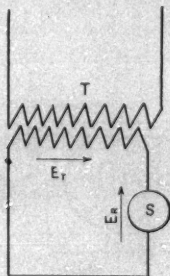


FIG. 6

E_r represents e.m.f. of transformation
 E_a " " " rotation

armature." The fact is, however, that the secondary current in the repulsion motor, beyond a certain speed of the armature, leads in respect to the primary electromotive force as in a transformer in which the secondary is working on self-induction and capacity or on self-induction and an over-excited synchronous

motor. The primary current, however, is always a lagging current in regard to its impressed electromotive force. The repulsion motor is like a combination of a transformer with a synchronous motor, the electromotive force of which is coincident in

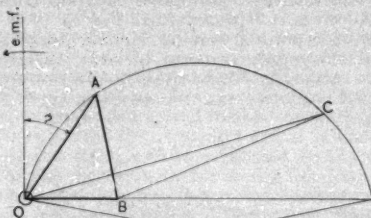


FIG. 7

- OB Magnetizing current
- OA Primary current
- AB Secondary current
- OC Primary starting current
- O Centre of circle

phase with the primary current (Fig. 6). The electromotive force of transformation E_T and the electromotive force of rotation, E_R (the latter is proportional to the speed of rotation) are in opposition and give a resultant electromotive force, which

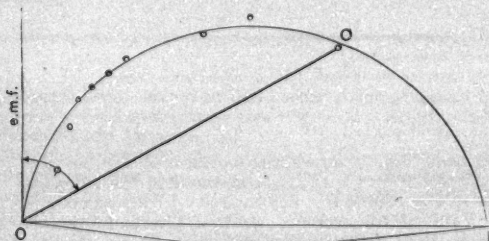


FIG. 8

- Vector diagram corresponding to Mr. Slichter's
- Curves of Repulsion Motor
- O C Starting current

produces the current through the ohmic resistance of the short-circuited armature. With Fig. 6 in mind it is easy to see that the secondary current leads the primary electromotive force at certain speeds of the armature. The polar diagram brings out

power-factor of the repulsion motor is lower than that of the series motor, a conclusion which, by the way, is diametrically opposed to that at which Mr. Steinmetz arrived; Mr. Lamme assumes that the inductance of the armature is negligible, and then draws a parallel between the straight-series motor and the repulsion motor as illustrated by Fig. 4 in this communication. Granting the assumption of a non-inductive armature (which is by no means permissible), Mr. Lamme's conclusions are right, but on that assumption the compensated series motor would give no better power-factor than the straight-series motor, which is obviously untrue. Mr. Lamme's reasoning and his conclusions have therefore to be modified, and instead of stating as he does that the power-factor of the repulsion motor is lower than the power-factor of the series motor, it should be stated that the power-factor of the repulsion motor is slightly lower than that of the compensated series motor, but considerably higher than that of the straight-series motor. From the English patent specification, it appears that Mr. Lamme's motor is a compensated series motor, corresponding to Fig. 3 in this communication.

In order to obtain high power-factors, it is necessary to design both the series motor and the repulsion motor on the same principles that have been found of importance in the design of induction motors. The successful series motor, however, has to be built with defined poles. Very good repulsion motors can be built for 60 cycles, and maximum power-factors of 90 to 95 per cent can be obtained even on small machines for comparatively low speeds. Such motors have very excellent series characteristics and can be used wherever the direct-current series motor is satisfactory.

COMMUNICATED AFTER ADJOURNMENT BY W. S. FRANKLIN.

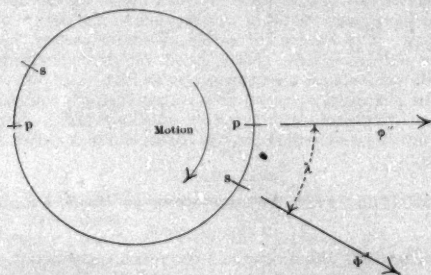
1. INTRODUCTION.

On May 19, 1903, the writer had the privilege of debating some points in alternating-current theory with Mr. Steinmetz before the Schenectady Branch of the INSTITUTE. During the visit which preceded this debate, the writer discussed the theory of the repulsion motor, at length, with Mr. Steinmetz. The writer had very recently worked out the theory of the repulsion motor, outlined below, and his results are in substantial agreement, with Mr. Steinmetz's; but knowing that Mr. Steinmetz had been working at the matter much longer, the writer urged him to present his work to the INSTITUTE, at an early date.

At the time of the conference, it was clear to both Mr. Steinmetz and the writer that the ideal theory as given in Mr. Steinmetz's paper, and as outlined below, did not take account of the very considerable distortion of the electromotive force wave due primarily to the fact that the two fluxes ϕ' and ϕ'' (see below) are not harmonically distributed around the periphery of the

machine. A first approximation to a correct theory is based upon the assumption that the fluxes are harmonic both in time and in space. A second approximation would be to consider the departure of the fluxes from harmonic space distribution, basing the calculations of this departure upon the first approximate solution by taking account of the magnetomotive forces generated in the several parts of the windings by the harmonic current values arrived at by the first approximation. Whether a third approximation, based upon calculated departures of the fluxes from harmonic variation in time, would be required for practical purposes, could be perhaps more cheaply answered by making a motor and comparing actual tests with second approximate calculations than by the arithmetical determination of the magnitude of the corrections introduced by the third approximation.

The development of the theory (first approximation) of the repulsion motor following is essentially the same as that of Mr. Steinmetz; it is given here because of the slightly different point of view, and because it is an example of the right-handed rotation ($r + jx$ instead of $r - jx$.)



2. OUTLINE OF THEORY OF REPULSION MOTOR.

Fig. 1 shows the axis of commutation ss of the armature (secondary-tap-axis), and the corresponding axis, pp , in the primary member of a repulsion motor. The primary current produces an alternating flux ϕ' at full primary frequency f' in the direction of the primary-tap axis, and the secondary or armature current produces an alternating flux ϕ'' at full primary frequency in the direction of the secondary-tap axis.

Let e' be the value of and E' the complex expression for primary impressed voltage.

f' the primary frequency.

i' the value of the primary current. The primary-current vector is taken as the reference axis and therefore i' is also the complex expression for the primary current.

ϕ' the value of the alternating flux due to the primary current i' .

θ' the phase-angle between E' and i' , positive when E' is ahead of i' .

Then

$$\phi' = k i' \quad (1)$$

in which k is the flux produced by unit primary current; and

$$E' = e' (\cos \theta' + j \sin \theta') \quad (2)$$

Furthermore, let Z be the number of conductors in the primary winding; the number of secondary conductors being assumed to be the same for the sake of simplicity.

r_1 the resistance of the primary.

x_1 the reactance value of magnetic leakage at primary frequency.

f' the speed of the armature in cycles per second.

i'' the value of secondary current and I'' its complex expression.

r_2 the secondary resistance.

θ'' the phase-angle between i' and i'' , positive when i'' is ahead of i' .

ϕ'' the value of the alternating flux due to the secondary current i'' , and Φ'' its complex expression.

Then

$$\Phi'' = k I'' \quad (3)$$

in which k has sensibly the same value as in equation (1); and

$$I'' = i'' (\cos \theta'' + j \sin \theta'') \quad (4)$$

To establish the general equations of the repulsion motor we must consider (a) the voltages induced in the primary. Placing the sum of such induced voltages equal to $-E'$ gives one equation; and (b) the voltages induced in the secondary. Placing the sum of such induced voltages equal to $+I''$ gives another equation.

Equation of Primary Voltages.—The total impressed primary voltage is made up of the following parts:

(a) The part $(r_1 + j x_1) i'$ used to overcome primary resistance and magnetic leakage reactance.

(b) The part $+j \cdot \frac{\phi' Z f'}{\sqrt{2}}$ used to balance the electromotive force induced in the primary by the pulsating flux ϕ' .

(c) The part $+j \cdot \frac{\Phi'' Z f'}{\sqrt{2}} \cdot \cos \lambda$ use to balance the electromotive force induced in the primary by the pulsating flux Φ'' .

Therefore:

$$E' = (r_1 + j x_1) i' + j \cdot \frac{\phi' Z f'}{\sqrt{2}} + j \cdot \frac{\Phi'' Z f'}{\sqrt{2}} \cdot \cos \lambda \quad (5)$$

Equation of Secondary Voltages.—The total electromotive force induced in the secondary is used to overcome secondary resistance; it is therefore equal to $r_2 I''$, and it consists of the following parts:

(a) The part $-j \cdot \frac{\phi' Z f'}{\sqrt{2}} \cdot \cos \lambda$ produced by the pulsations of the flux ϕ' .

(b) The part $-j \frac{\Phi'' Z f'}{\sqrt{2}}$ produced by the pulsations of the flux Φ'' .

(c) The part $+\frac{\phi' Z f''}{\sqrt{2}} \cdot \sin \lambda$ produced by the motion of the secondary relative to the flux ϕ' .

Therefore:

$$r_2 I'' = \frac{\phi' Z f''}{\sqrt{2}} \cdot \sin \lambda - j \cdot \frac{\phi' Z f'}{\sqrt{2}} \cdot \cos \lambda - j \cdot \frac{\Phi'' Z f'}{\sqrt{2}} \quad (6)$$

Equations (5) and (6), together with the equations of definition (1), (2), (3) and (4), are the fundamental equations of the repulsion motor. The assumptions upon which these equations rest and the extent to which these assumptions deviate from the conditions which really exist in a repulsion motor are discussed later. Three things only need be said to clear up the derivation of equations (5) and (6); namely, (a) only that component of a flux which is parallel to a tap-axis produces electromotive force by pulsation; (b), only that component of a flux which is at right angles to a tap-axis produces electromotive force by motion; and (c), all induced electromotive forces involved in equations (5) and (6) are of the same frequency f' . This is due to the fact that the electromotive forces induced in the secondary are referred to the stationary tap-axis *SS* Fig. 1; the electromotive force (or current) in a given moving secondary wire may be thought of as having a frequency f'' , while its amplitude varies at frequency f' . This is equivalent to the superposition of two genuine alternating electromotive forces of which the frequencies are $f' + f''$ and $f' - f''$ respectively.*

Substituting the values of ϕ' , Φ'' , E' , and I'' from equations (1), (2), (3) and (4) in equation (5), we have:

$$\begin{aligned} e' \cos \theta' + j e' \sin \theta' &= r_1 i' + j x_1 i' + j \cdot \frac{k Z f'}{\sqrt{2}} \cdot i' \\ &+ j \cdot \frac{k Z f'}{\sqrt{2}} \cdot \cos \theta'' \cos \lambda \cdot i'' \end{aligned}$$

* $2 [\cos \omega' t] \cdot \cos \omega'' t = \cos (\omega' + \omega'') t + \cos (\omega' - \omega'') t$.

$$-\frac{kZf'}{\sqrt{2}} \cdot \sin \theta'' \cos \lambda \cdot i'' \quad (7)$$

Substituting the values of ϕ' , Φ'' , E' and I'' from equations (1), (2), (3) and (4) in equation (6) and we have:

$$r_2 i'' \cos \theta'' + j r_2 i'' \sin \theta'' = \frac{kZf''}{\sqrt{2}} \cdot \sin \lambda \cdot i' \quad (8)$$

$$-j \cdot \frac{kZf'}{\sqrt{2}} \cdot \cos \lambda \cdot i' - j \frac{kZf'}{\sqrt{2}} \cdot \cos \theta'' \cdot i'' + \frac{kZf'}{\sqrt{2}} \cdot \sin \theta'' \cdot i''$$

Let

$$\frac{kZf'}{\sqrt{2}} = a$$

$$\frac{kZf''}{\sqrt{2}} = b$$

Then, separating real and imaginary parts, equation (7) becomes

$$\left. \begin{aligned} e' \cos \theta' &= r_1 i' - a \sin \theta'' \cos \lambda \cdot i'' \\ e' \sin \theta' &= x_1 i' + a i' + a \cos \theta'' \cos \lambda \cdot i'' \end{aligned} \right\} \quad (9)$$

and equation (8) becomes:

$$\left. \begin{aligned} r_2 \cos \theta'' \cdot i'' &= b \sin \lambda \cdot i' + a \sin \theta'' \cdot i'' \\ r_2 \sin \theta'' \cdot i'' &= -a \cos \lambda \cdot i' - a \cos \theta'' \cdot i'' \end{aligned} \right\} \quad (10)$$

The torque, power-output, power-intake, power-factor, and efficiency curves of the repulsion motor plotted on speed-base (f'') may be calculated from equations (9) and (10) as follows:

In the first place, r_1 , e' , a , and x_1 are known from the design of the motor and from the given value and frequency of the primary voltage.

In the second place, λ and r_2 may be each varied at will, and therefore the curves are to be plotted for each of a series of arbitrarily assigned values of λ and r_2 . In the third place, f'' may be taken as the independent variable, upon which the tracing of the curves depends, and the values of torque, power-output, power-intake, etc., calculated for various assigned values of f'' .

Thus, from an assigned value of f'' the value of b is known. From this, together with the known values of r_1 , e' , a , and x_1 , and the chosen values of λ and r_2 , the values of i' , i'' , θ' , and θ'' are determined by equations (9) and (10). Then for the given speed f'' we have:

$$\begin{aligned} \text{power-intake} &= e' i' \cos \theta' \\ \text{power-factor} &= \cos \theta' \\ \text{power-losses} &= i'^2 r_1 + i''^2 r_2 + \text{core losses.}^* \end{aligned}$$

*Eddy current and hysteresis losses are to be calculated independently of the above ideal theory, from the known value of ϕ' , Φ'' , λ , f' and f'' . See following discussion of Mr. Steinmetz's paper.

$$\begin{aligned}
 \text{power-output} &= \text{power-intake minus losses} \\
 \text{torque} &= \text{power-output} \div 2\pi f'' \\
 \text{efficiency} &= \text{power-output} \div \text{power-intake}.
 \end{aligned}$$

The above outline of the method of calculating the characteristic curves of the repulsion motor is sufficiently simple as a matter of theory but it is quite laborious as a matter of fact; and therefore certain of the terms of low value may be advantageously discarded in the final algebraic expressions for i' , i'' , θ' and θ'' .

(a) It may be worth while to point out the correspondence between Mr. Steinmetz's quantities Z and x (see page 79 of Mr. Steinmetz's paper), and the quantities which the writer represents by a and b , especially inasmuch as Mr. Steinmetz seems not to have specified the meaning of his symbol x .

Mr. Steinmetz's Z is identical with a , and Mr. Steinmetz's x (see equation (4), page 79) is equal to $f'/f'' \times b$.

When magnetic leakage is not very great, an ampere-turn, whether on the primary or secondary, produces sensibly the same amount of flux through the secondary, and in this case Mr. Steinmetz's Z and x are identical, if, as is assumed for the sake of simplicity, the primary and secondary have the same number of conductors.

(b) Mr. Steinmetz seems to say on page 74 that inductance-reactance in the secondary of a transformer becomes capacity-reactance in its effect upon the primary! The fact is that the decrease of lag of the primary current of a transformer due to load on the secondary is essentially the same effect as the decrease of lag of total current when a circuit of comparatively low inductance is connected in parallel with a highly inductive circuit.

Aside from difference in size or in design, it is not clear why Mr. Steinmetz's Fig. 3 should have a higher power-factor than his Fig. 2 (this matter is considered in detail under *c*) and even if Mr. Steinmetz's apparent statement regarding the relative power-factors of Figs. 2 and 3 is correct, his explanation is not convincing.

The series motor provided with a Ryan compensating winding to annul armature reaction is, when operated by alternating current, identical in its action to the repulsion motor, save in one respect, which is mentioned under *d*.

Consider, for example, Mr. Steinmetz's Fig. 5, which is equivalent to his Fig. 6. This constitutes a repulsion motor. The same structure with all three windings connected in series would be a series motor with a Ryan compensating winding. Let us consider the correspondences between the two machines on the assumption that coil resistances are zero; that magnetic leakage is zero; and that magnetic reluctance of core is zero.

Under these conditions the compensating winding A_2 and the armature winding together constitute an ideal transformer (zero

resistance, zero magnetic leakage, and zero magnetic reluctance*) so that the current in the short-circuited armature of Fig. 5 is exactly equal in value and opposite in phase to the main current in winding A_2 , and the electromotive force induced in the armature by motion is transformed to or exactly reproduced in winding A_2 , except that its phase is reversed.

Now, the reversal of phase is merely a matter of reversing connections so that the current induced in the armature is exactly the current which would flow through the armature if it were properly connected in series with the two field windings; and the electromotive force which opposes the flow of current through the two field windings A_1 and A_2 in Fig. 5 is exactly the electromotive force which would oppose the flow of current if the armature were properly connected in series with the two field windings.

Under the above-mentioned ideal conditions, the motor action of the device is exactly the same, its power-factor is the same; in fact, everything is the same, with the one exception mentioned under *d*, be the device connected as a repulsion motor or as a series motor.

So much for the ideal case; but what are the effects of coil resistances, magnetic leakage and core reluctance? These effects vitiate the motor action and they vitiate motor action more when the device is connected as a repulsion motor than when the device is connected as a series motor. This may be made clear by the following simple considerations:

When all the windings are connected in series the current is the same in all and the armature current is exactly in phase with the torque-producing flux. When the armature is short-circuited and the armature current produced by transformation from the winding A_2 , then (*a*) the armature current (secondary) is slightly less in value than the main current (ratio of primary to secondary terms equal to unity) on account, primarily, of core reluctance; and (*b*) the armature current differs in phase slightly from the main current and therefore from the torque-producing flux on account primarily of coil resistances and magnetic leakage.

Therefore, other things being equal, the torque is lessened on account of coil resistances, magnetic leakage, and core reluctance.

(*d*) The one difference between the compensated series motor and the repulsion motor is the above described transformer action and the production of cross-flux (M_2 in Mr. Steinmetz's paper) associated therewith.

This transformer action is, however, under ideal conditions entirely independent of motor action, whereas under practical conditions this transformer action, itself incomplete, detracts from the action of the structure as a motor.

*It would be well if the "practical man" realized that once in a while, at least, the "theoretical man" sets forth ideal conditions in order that a practical matter may be made simple enough for the practical man to understand.

When the device (Fig. 5) is connected as a compensated series motor, no cross-flux is produced and the cross reluctance of the core may be made high, perhaps with advantage; certainly with saving of material.

(e) There is one point wherein the repulsion motor has an advantage over the compensated series motor, and in regard to which the writer agrees with Mr. Steinmetz. This is in the matter of hysteresis and eddy-current losses in the armature core.

In the compensated series motor the armature is subjected to reversals of magnetization and the hysteresis and eddy-current losses are high.

In the repulsion motor the effect of the cross-flux is to produce a resultant magnetization of the armature core, which rotates at synchronous speed. This rotating magnetization is elliptical below and above synchronous speed of the armature, and circular at synchronous armature speed, so that in the repulsion motor the hysteresis loss in the armature core is large at standstill; it decreases to zero at synchronous speed, and increases again at speeds above synchronism.

The writer does not, however, agree with Mr. Steinmetz in his statements concerning the variation with speed of hysteresis loss in the armature core of the series motor. This loss is large at standstill, it decreases to about $\frac{1}{2^{1.5}}$ as great a value at synchronous speed and increases again at speeds above synchronism.

[COMMUNICATED AFTER ADJOURNMENT].

BY B. G. LAMME.

It appears that there is a possible misunderstanding of the use of the term "straight-series" as applied by the writer to one class of single-phase motors. By this term the writer means motors in which the armature and field windings are all directly in series, and in this class is included motors with compensating windings in the poles. In the discussion of Mr. Steinmetz's paper the writer referred to the armature as being practically non-inductive and the field as being the inductive element. For best proportions such a motor would naturally be of the compensated type, and the writer's discussion was based primarily upon "straight-series" motors having compensating windings, although no direct statement to that effect was made. The series motor without compensating winding would undoubtedly have considerably higher armature self-induction than the compensated motor, and would naturally have lower power-factor.

DISCUSSION ON ALTERNATING-CURRENT RAILWAY MOTORS AT PITTSBURG, FEBRUARY 2, 1904.

V. KARAPETOFF: The connection between ordinary direct-current series motor and the modern types of alternating-current commutator motor seems to be as follows:

First of all a neutralizing winding, N , was brought in to compensate for the armature reaction (Fig. 1). Then the idea came, that in an alternating-current motor induction can be used instead of conduction. This gave two different schemes (Fig. 2 and Fig. 4), with either the armature or the neutralizing winding as secondary. In the first of these "transformer-type" motors (Fig. 2) both field coils have the same current, and can be re-

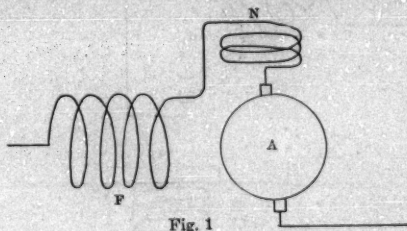


Fig. 1

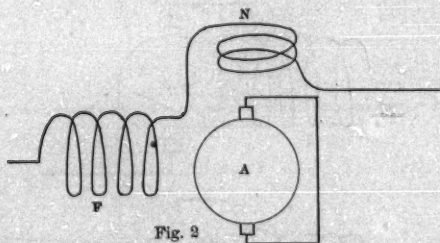


Fig. 2

placed by a single coil having the resultant number of ampere-turns (Fig. 3); this is the repulsion motor. The second type (Fig. 4) can be simplified by using the armature winding itself as a neutralizing coil. To that end two auxiliary short-circuited brushes, $N N$, must be set at 90° to the principal brushes (Fig. 5); this is the principle used in the Winter-Eichberg and in the Latour motors.

The theory of the repulsion motor, as given by Mr. Steinmetz, is based upon two equations:

$$e_o = Z (I + I_1 \cos w) + I Z_o$$

and

$$0 = -a x I \sin w + Z (I_1 + I \cos w) + Z_1 I_1$$

(page 80 of his paper).

The first of these equations expresses Ohm's law applied to the primary circuit of the motor, and the second, to the secondary circuit, if the e.m.f., $a \times I \sin w$, induced by rotation, be considered as the applied e.m.f. of secondary circuit. All the rest of the theory simply consists in algebraical transformations of these equations to get the power-factor, the input, torque, speed, and so on.

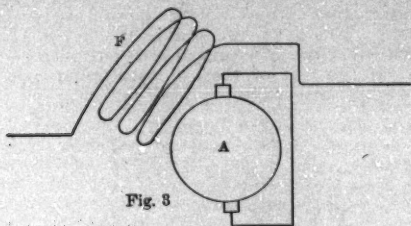


Fig. 3

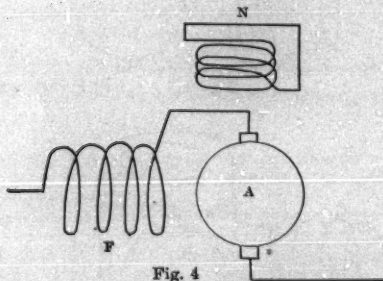


Fig. 4

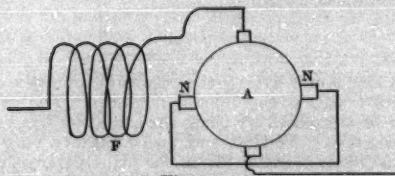


Fig. 5

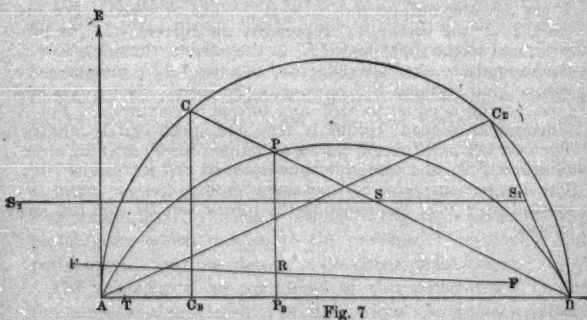
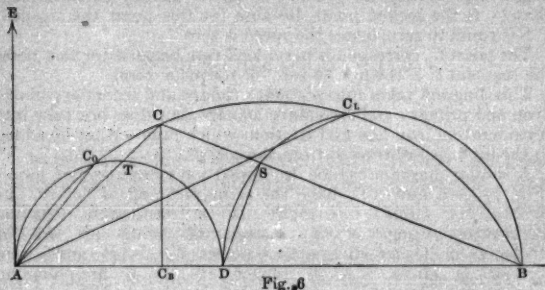
An analogous equation for straight-series motor can be given (one equation, because there is but one circuit). Let Z_m be the impedance of the field-magnet system, and Z_a the combined impedance of armature + neutralizing coil. Then with the same notations as in Mr. Steinmetz's paper

$$e_o = a \times I + I (Z_m + Z_a);$$

that is, the impressed voltage minus the counter e.m.f. of rotation is absorbed by the impedance of the motor.

By similar algebraical transformations, a complete theory of straight-series motor can be developed and formulas given for torque, speed, power-factor, and so on.

An excellent performance diagram of the repulsion motor was recently given by Mr. Osnos in the *Electrotechnische Zeitschrift*, 1903, No. 44; this diagram is



shown in Fig. 6. AE is the direction of the impressed voltage, AC_1 is the current with the armature locked, drawn at an angle EAC_1 , corresponding to the power-factor when so locked. AC_0 is the current at no load, and EAC_0 is the corresponding phase-angle. Draw an arc of circle, passing through C_0 , C_1 , and the origin A . This is the circle of input, and the angle EAC corresponds to the power-factor at any particular load. Ordinate CC_0 , being the working component of the current, represents the input to the motor.

Describe the semicircle $BC_L D$, which has its centre on AB , perpendicular to AE , and passes through B and C_L . Then on AD , as a diameter, describe a second semicircle $AC_o D$. The first of these semicircles is the circle of speed and the second is the circle of torque. Thus, for a load C , the speed is represented by the ratio $\frac{CS}{SD}$, and torque by the product $CA \times CT$.

Besides, DC represents the secondary current in phase and magnitude (reduced to primary circuit). It may be easily seen that C_L is the locked point, because for this point the segment CS is equal to zero, hence the speed is zero.

The point C_o corresponds to no-load run, because for this point the segment CT is equal to zero, or torque is zero.

This diagram takes into account primary and secondary ohmic drop and primary and secondary leakage, but does not take into consideration iron loss and friction, which must either be added to the input or subtracted from the output.

A similar diagram can be developed for straight-series motor (Fig. 7), AE and AC_L have the same meaning as before, but $AC_L B$ circle of input is a semicircle, having its center upon AB , instead of being an arc of circle, as in Osnof diagram. Connect C_L to B and draw the arc of circle APB tangent to $C_L B$ and passing through A . Then draw any line parallel to AB , as SS_o . APB is the circle of output and $S_1 S_2$ is the line of speed. For any load, as C , the vector AC represents the current; CC_o is proportional to the input and PP_o to the output; the angle EAC corresponds to the power-factor; abscissa AC_o measures the torque, and segment SS represents the speed. For C_L (locked point) speed is equal to zero, and torque is maximum. For A (theoretical no-load) torque is zero, and speed equals infinity. The iron loss and friction can be accounted for by drawing a certain line, FF , and taking output equal to PR instead of PP_o . The torque can also be measured from a certain point, T , instead of A , AT representing the torque lost by iron loss and friction.

SINGLE-PHASE RAILWAYS.

BY W. A. BLANCK.

In perhaps no line of electrical industry has there been greater activity than in that of interurban railway construction. At the present time in the United States, particularly in the Central States, this development has reached a magnitude entirely beyond the expectations of the most sanguine of a decade since. In fact this development has gone so far that in some sections most of the best propositions are already exploited; however, there are still a great many, which, while of doubtful value with the present direct-current system—involving the use of synchronous converter sub-stations and low trolley pressure—would be very profitable if a system could be developed that would materially reduce the cost. For some time the perfecting of the single-phase motor has been suggested as the solution of this problem, since the application of this motor to electric traction means a great reduction in the cost of the transmission system. The present activity in the evolution of the single-phase railway motor gives added interest to the problem of developing and perfecting all the other details of the single-phase system.

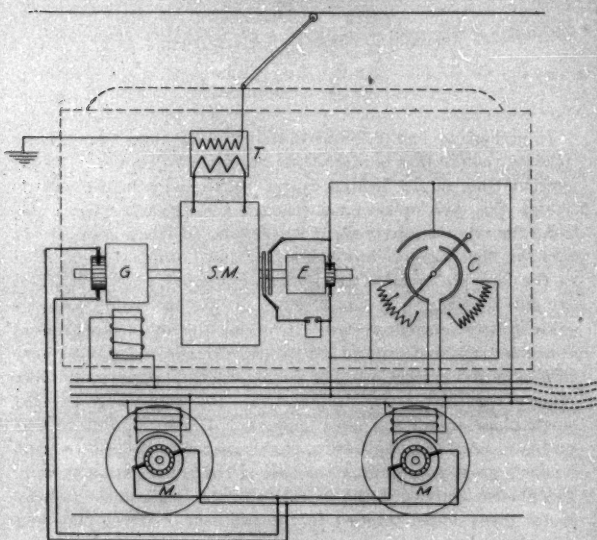
The subjects to be considered in this paper are: 1 The fundamental characteristics of the various single-phase railway motors; 2 Certain details of line construction; and 3 The comparative cost of installing typical power-houses, sub-stations in power-houses, transmission lines, sub-stations along the road, trolley lines and feeders, and bonding of rails for a 60-mile, single-track interurban railway on direct-current and alternating-current systems.

The first problem to be solved is the development of a single-phase alternating-current motor that will operate satisfactorily

under the conditions imposed by railway service. The importance of this problem was early recognized and its solution has been sought by many of the ablest engineers both here and abroad.

The attention given the single-phase system by the technical press has brought it prominently before engineers, but a short resumé of the present state of the art may not be out of place.

SYNCHRONOUS MOTOR



WARD LEONARD

FIG. 1.

THE SYNCHRONOUS MOTOR.

The synchronous motor requires a separately-excited field, has no starting torque, and cannot be run at variable speed, therefore its direct application to railway traction is impossible. It has been proposed by Ward Leonard to use the synchronous motor in combination with a direct-current generator, to furnish direct-current to standard motors. This idea shown in Fig. 1, which is lettered to be self-explanatory.

THE INDUCTION MOTOR.

In respect to starting and speed-control, the induction motor shows the same peculiarities as the synchronous motor; to overcome these peculiarities, Bion J. Arnold proposes a suitable combination of an induction motor with a mechanical energy-storage contrivance, this contrivance consisting of an air-compressor and tank. The various members of this combination are indicated in Fig. 2. In this system both

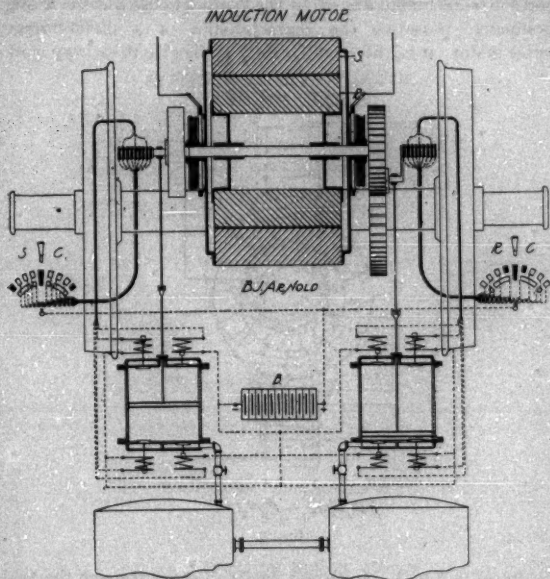


FIG. 2.

parts of the motor are free to rotate, and they maintain a constant relative speed. The rotor is geared to the axle and also connected to one air-cylinder. The stator is connected to a second air-cylinder, in which, when the car is running at less than full speed, air is compressed. When the car is at full speed the stator is at rest and there is no compression. By admitting air to this cylinder and rotating the stator in the same direction as the rotor the car can be run at more than

synchronous speed. This combination, with the induction motor continually running, makes it possible to store energy when the car is coasting or stopped, and to use this energy when the car is accelerated. Further, this system allows the operation of the car by compressed air for a limited time, should it be desirable to run without overhead conductor.

THE SERIES MOTOR.

The alternating-current series motor, as proposed by Lamme and Finzi and manufactured by the Westinghouse Electric & Mfg. Company, possesses the characteristics of a direct-current series motor; it is, therefore, directly applicable to railway work.

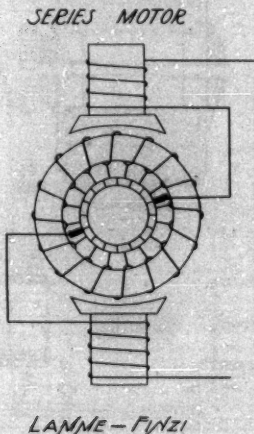


FIG. 3.

As shown in Fig. 3, the current passes in series through the field and armature. The armature is similar to the ordinary direct-current drum-type armature with commutator. As the direction of rotation in the direct-current series motor is not dependent on the direction of the current, it is evident that the motor will operate with alternating as well as with direct-current.

Since the series commutator motor cannot be operated at high-pressure, it is necessary to use a step-down transformer in connection with a high-pressure trolley, thus increasing the weight of the car equipment.

THE REPULSION INDUCTION MOTOR.

The repulsion induction motor developed by Steinmetz and Schöler and manufactured by the General Electric Company, shows in general the same characteristics as the straight-series motor; it can be operated directly from the high-pressure trolley, since, as indicated in Fig. 4, the armature is independent of the field. The current is induced in the armature by transformer action and can be of any desired pressure. The brushes are short-circuited and placed at an angle to give the best running conditions.

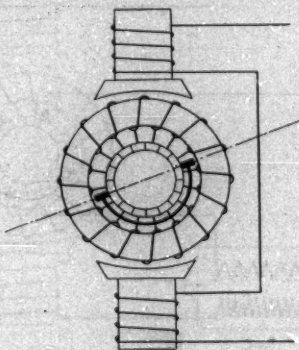
REPULSION INDUCTION MOTOR*STEINMETZ-SCHÖLER*

FIG. 4.

THE REPULSION SERIES MOTOR.

The repulsion series motor developed by Winter-Eichberg and built by the Union Electric Company, Berlin, Germany, is similar to the repulsion induction motor with the addition of a second set of brushes, displaced 90° from the short-circuited brushes, as shown in Fig. 5. Through these brushes current is supplied by a series transformer; this is done for the purpose of decreasing the sparking at less than synchronous speed, and securing the important additional advantage of raising the power-factor nearly to unity.

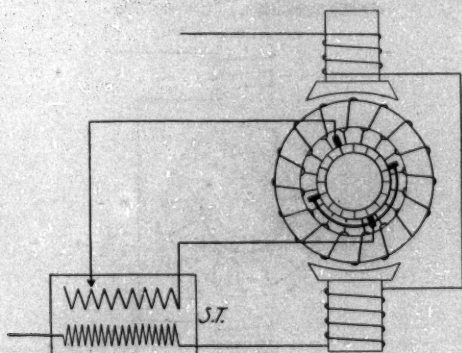
CONTROLLERS.

In general, the operation of the last three motor systems is effected by master controllers operated to get the desired combinations. To obtain the voltage variation necessary for speed-control, induction regulators are used in all three cases, thus avoiding the losses consequent to the rheostatic control of the direct-current system.

CAR WIRING.

To protect passengers and crew from the high pressure used in this system, it is necessary that the wiring should be done in

REPULSION SERIES MOTOR



WINTER - EICHBERG

FIG. 5.

metallic conduit; this should be connected to the trucks so that any defect in the insulation of the circuit will result in the tripping of the automatic circuit-breaker in the car. Moreover, it will be necessary to insulate the steps and hand-rails to guard the passengers from shocks, which might occur during wet weather or from a car standing on a dirty rail.

TROLLEY BOW.

With the high-pressure working conductor it is necessary to provide against any possible short-circuiting of the trolley and its suspensions. On account of the serious results which would follow the slipping of the trolley pole so common in the present system, a suitable bow must be used instead. This trolley bow is mounted on a well-insulated platform on the roof of the car;

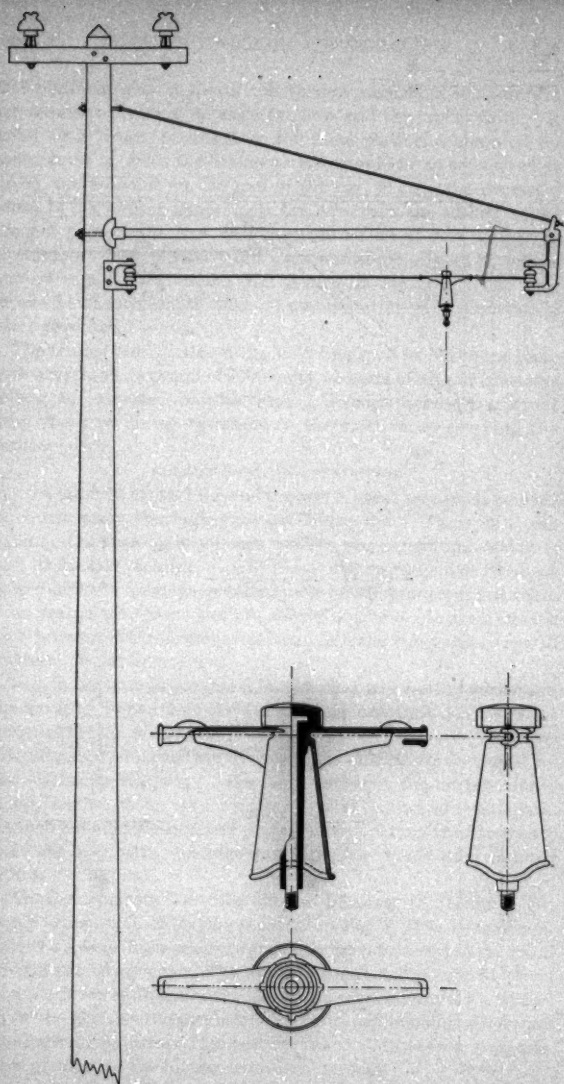


FIG. 6.

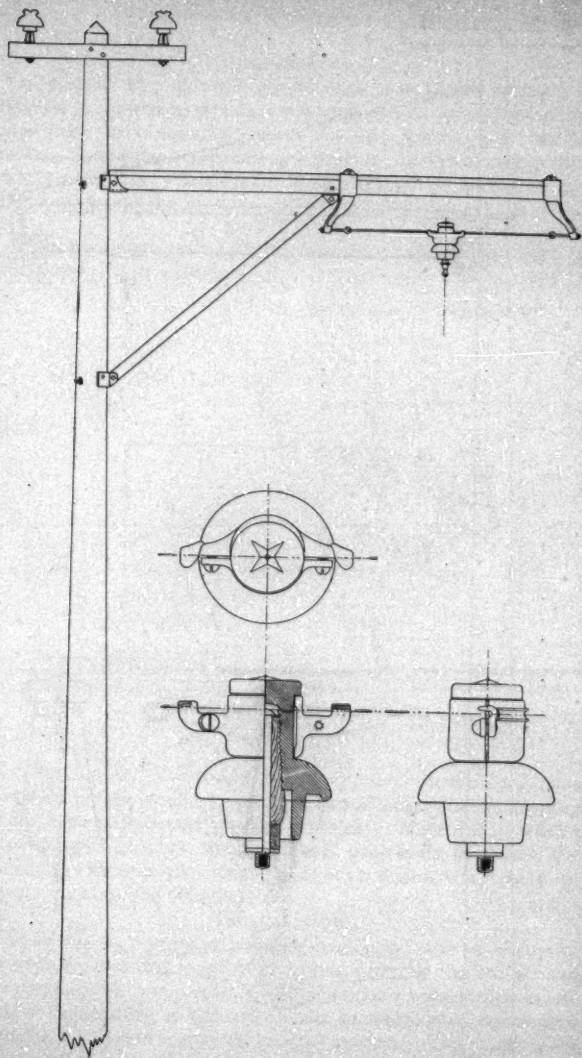


FIG. 7.

this platform also supports the springs necessary to maintain the requisite pressure between the bow and the trolley wire. A small air-cylinder, mounted on the same platform, operated by compressed air from the brake system, should be so connected as to lay the bow flat on the roof of the car, in case the necessity arises to disconnect temporarily the bow from the trolley. The contact part of the bow can be made either of soft copper or aluminum. The necessary lubrication is accomplished by grease applied in a slot extending the length of the bow. The bow should be of such length that no manipulating will be necessary when reversing the car.

The trolley bow in use on the Valtelina road in Northern Italy with a working pressure of 3000 volts, consists of copper cylinders rolling in insulated ball-bearings. Brushes take the current from these revolving cylinders to the steel tubes carrying the contact-piece.

TROLLEY-LINE CONSTRUCTION.

In order to protect life and property, great care must be used in constructing the high-pressure trolley line. There is a prevailing idea that high-pressure trolleys are dangerous, and it is said that this condition will retard the development of alternating-current railways operated over public property; but there is no reason why these trolleys should not be made as safe as the high-pressure distributing systems of lighting companies, now so common on public property.

It is important to provide a hanger that will readily withstand the working pressure of the system, and one that can be easily replaced in case of mechanical or electrical defects. Fig. 6 shows a trolley-line construction with hangers similar to that used on the Valtelina Railway. The bolt carrying the trolley-clamp is surrounded by an insulating compound, called ambroine, and set into a malleable-iron bell provided with clamp-arms to secure it to the span-wire. A cast-iron cap-screw holds the insulated bolt firmly in place.

Another construction used on the Lansing, St. Johns & St. Louis Railway, in Michigan, is shown in Fig. 7. The hanger consists of a special high-pressure glass insulator fastened to the span-wire in the usual way. The working conductor is carried by an iron pin inserted in a wooden sleeve, on which is turned a thread to fit the glass of the insulator. A thin lead bushing allows the insulator to be firmly clamped by the malleable-iron supports, thus preventing the hanger from jarring loose.

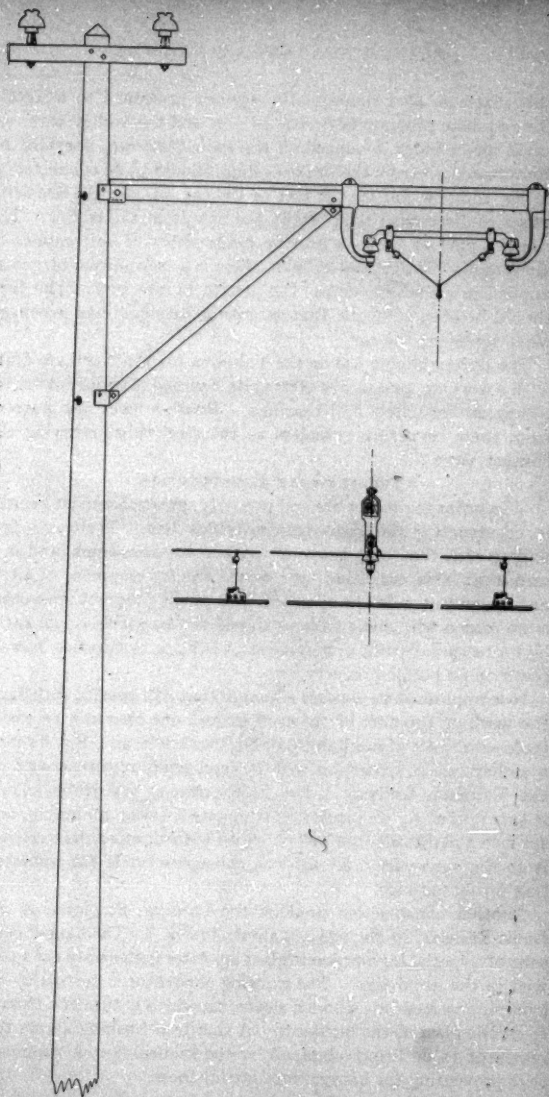
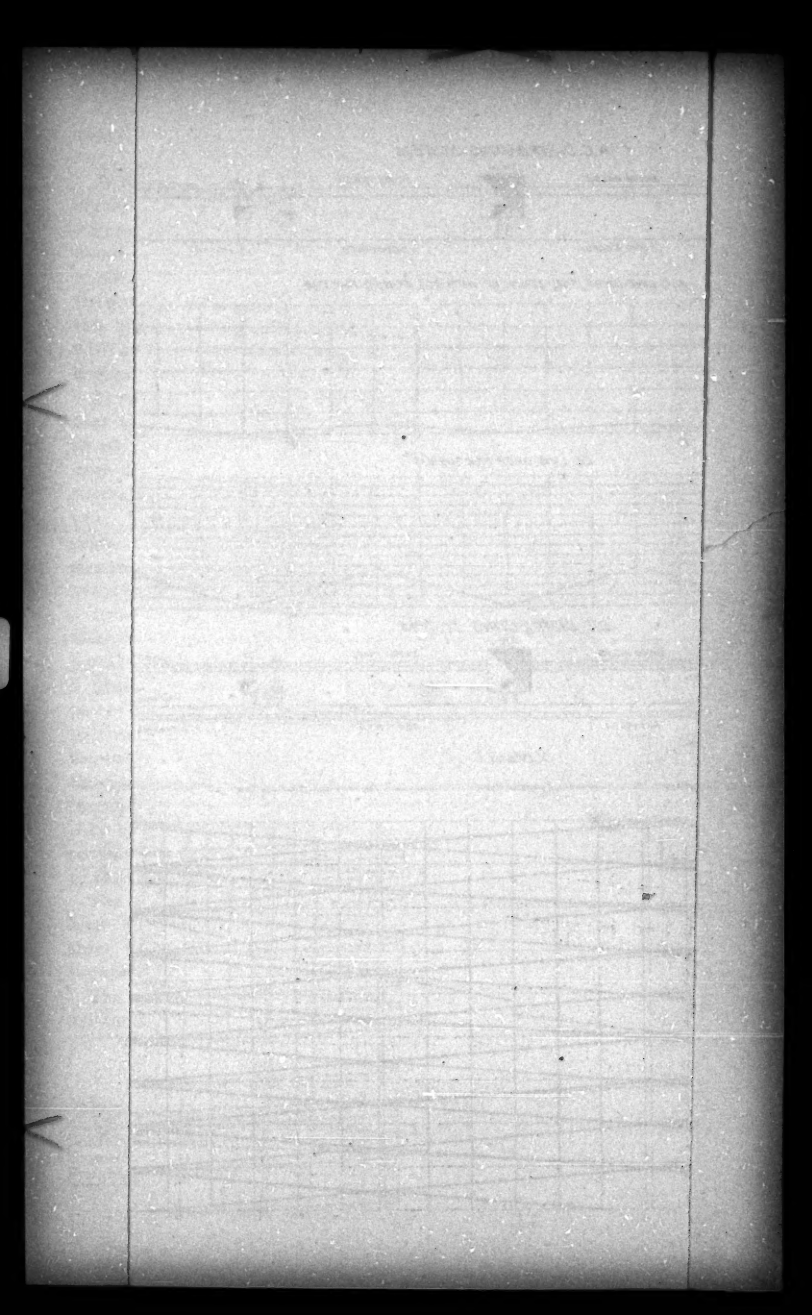
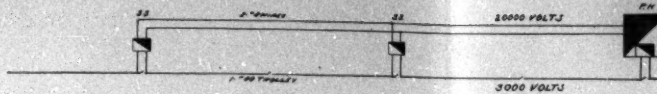


FIG. 8.



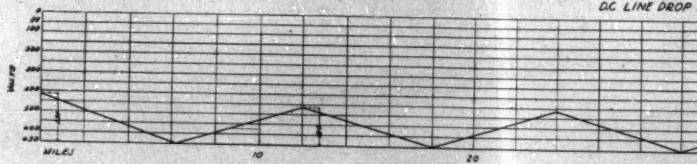
A.C. DISTRIBUTION



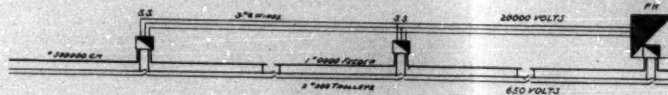
A.C. LINE DROP FOR 300 K.W.



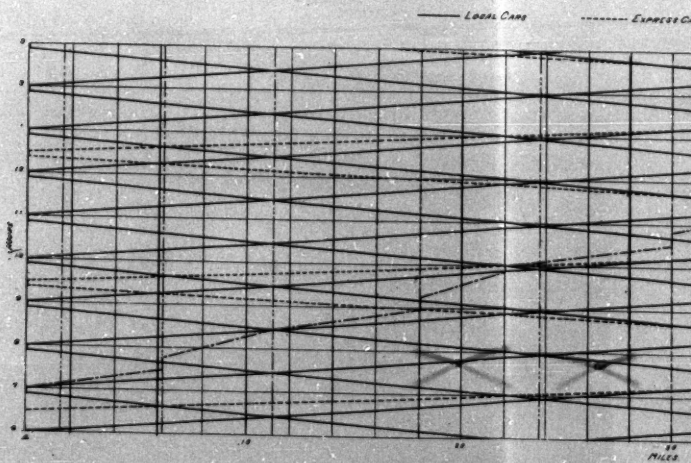
D.C. LINE DROP



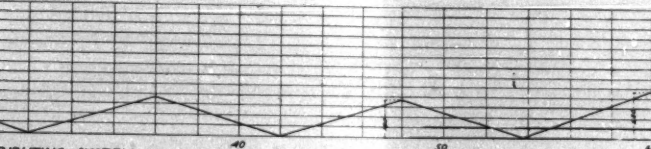
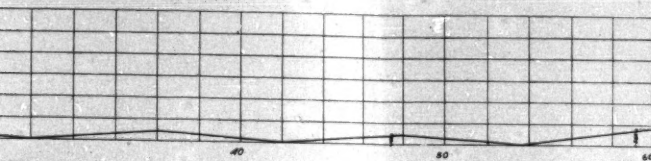
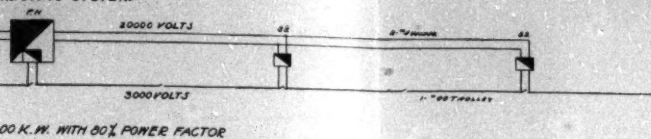
D.C. DISTRIBUTION



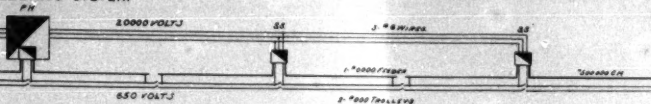
SCHEDULE



DISTRIBUTING SYSTEM

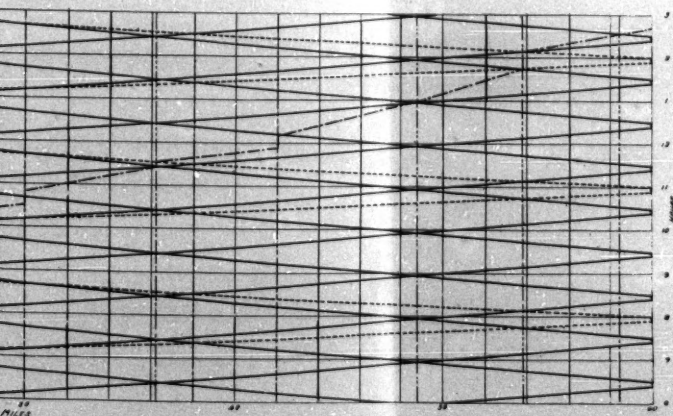


DISTRIBUTING SYSTEM



SCHEDULE

Express Cars ——— Freight and Baggage Cars



V
1

If the road operates on a public highway, special precautions should be taken to avoid accident. One solution is shown in Fig. 8; in this the working conductor is suspended at intervals of about ten feet from two steel wires. In case of a mechanical break in the trolley wire it is evident that the end cannot reach the ground or injure passers-by. It might be noted in passing that this construction increases the carrying capacity of the trolley with but slightly greater investment. A construction somewhat similar to this is in use on the single-phase railway near Berlin.

In regard to returning current through the rails, it may be said that with the proposed frequency of 25 cycles per second and the small current required with the higher pressure, this loss will be even smaller than in direct-current railway work, so that for normal interurban service it will be sufficient to bond only one rail. This has the advantage, greatly to be desired in many cases, of leaving the other rail free for the purpose of block signals. Furthermore, the evils of electrolysis are completely avoided with the alternating-current system.

In order to consider more in detail the relative merits of the alternating-current and direct-current systems of distribution, parallel computations and diagrams may be made for the case of a 60-mile, single track, interurban road. We shall assume the power-house to be located at the centre of the line and to contain one sub-station, and that four sub-stations are located at equal intervals on the line, as shown in Fig. 9. Although the alternating-current system will not require sub-stations at as frequent intervals as in the direct-current system, they are retained on account of the advantage derived from sectionalizing the line, and the better distribution of power due to the larger number of feeding points.

The schedule proposed requires five local cars having one-hour headway; one express-car, making the round trip in three hours, and one freight- and baggage-car making the trip between the two terminals in about eight hours.

The average power required by the various cars in kilowatts will be as follows:

	Weight in tons.	Schedule speed in miles per hour.	Watt- hours per ton-mile.	Kilowatt- hours per trip.	Average power in kilowatts
Local-car.....	30	25	80	144	60
Express-car.....	35	42.8	110	231	165
Freight-car.....	30	12	70	126	25

With the schedule outlined above, the average load on all five sub-stations will be about 500 kw., or 100 kw. per sub-station, while the maximum load per sub-station under certain conditions

— ALTERNATING CURRENT RAILWAY SYSTEM —

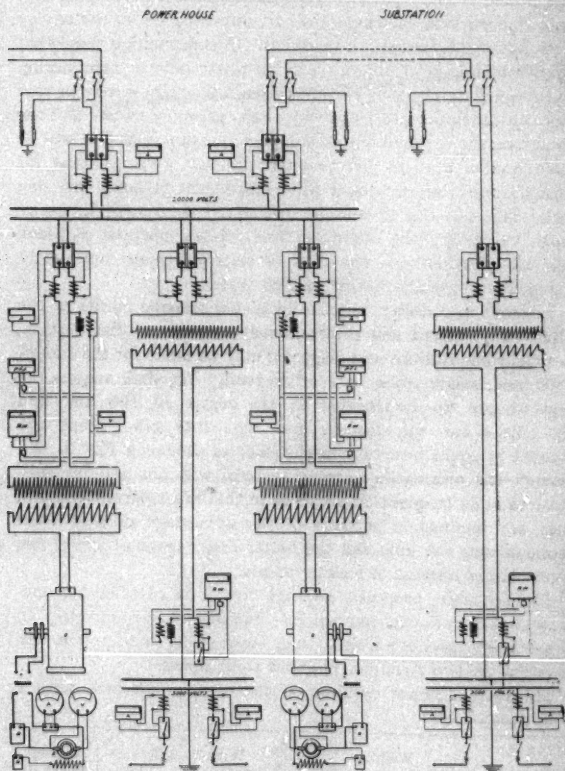


FIG. 9.

is 450 kw., for instance, when the express-car is starting and two locals are running in one section. With a proper momentary overload allowance this assumed condition will require one

300-kw. synchronous converter per sub-station in the direct-current system. In the alternating-current system, however, a static transformer of 200-kw. capacity per sub-station will be ample. The maximum load at the power-house will be 800 kw. and two 400-kw. units will suffice, if for the purpose of this comparative study no reserve capacity be provided either in power-house or sub-stations.

Some idea of the relative simplicity of the transmission systems in the two cases may be obtained from a consideration of the accompanying wiring diagram, Fig. 10, showing the apparatus and connections required in each case. In both cases step-up transformers raise the total generator output to the high transmission pressure, and a step-down transformer set is placed in the power-house. Although the power-house sub-station could take its supply directly from the generators, it is preferred to use one general form for all sub-stations, thus avoiding special switching arrangements. For the three-phase transmission lines of the direct-current railway system, three No. 6 wires are assumed, and for the single-phase transmission line two No. 4 wires, costing respectively \$10 000 and \$11 500.

The proportions of the distributing-system have been calculated for the following conditions: for the direct-current system it is assumed that the maximum drop in line pressure in the case of a car starting at its maximum distance from sub-stations is approximately 200 volts, or about 30%. This condition can be obtained by installing two No. 000 trolley wires and No. 0000 feeder capacity between sub-stations, and 500 000 circular mils feeder for the stub-ends. The cost of the copper under these conditions will be about \$95 000.

For the alternating-current system the size of the trolley wire has been determined from mechanical rather than from electrical considerations. A No. 00 grooved trolley wire has been assumed installed throughout the length of the line, since for this class of service it is not practicable to use smaller sizes. The cost of the copper in this case will be \$21 500.

In determining the drop for this system, 80% power-factor is assumed. It will be noted that the maximum drop under the same conditions as above mentioned will be 190 volts between sub-station, or 6.25%, and 380 volts on stub ends, or 12.5%. This shows a considerable advantage in favor of the alternating-current system.

At present the alternating-current motor weighs somewhat

more than the direct-current motor, and operates at a slightly lower efficiency. However, the smaller efficiency of the alternating-current motor is more than counterbalanced by the small

— DIRECT CURRENT RAILWAY SYSTEM —

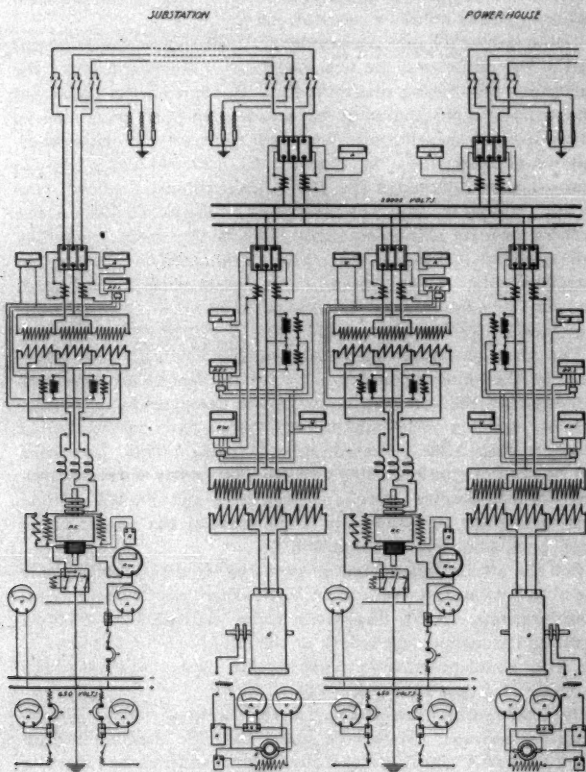


FIG. 10.

percentage loss in the alternating-current distributing system. And, furthermore, with the rapid development now taking place in the alternating-current motor, it is safe to assume that in the

very near future its characteristics as to weight and efficiency will soon equal those of the direct-current motor, thus making the advantage of the alternating-current railway system still more evident.

An idea of the relative first cost for the two systems may be obtained by arranging in parallel columns the cost of the various items; this is done in the accompanying table and diagram.

It is not necessary to take up in detail all the items, as they speak for themselves, but it may be of interest to note some items in which the costs vary more widely:

The single-phase generators, as would be expected, cost nearly 30% more than three-phase generators, this increase in cost amounts to \$5000. Small savings on switchboard and wiring reduce the total for the power-house \$3500 in favor of the direct-current system.

For the sub-station in the power-house, principally on account of saving in converter and transformer capacity, the balance is \$8000 in favor of the alternating-current system.

The transmission systems are approximately the same, there being \$2000 in favor of the alternating-current system.

In the alternating-current distributing system, while the suspension of the trolley is noticeably more expensive than in the direct-current system, on account of special insulators, the immense saving in copper gives a balance of \$78 000 in favor of the alternating-current system.

The necessity of bonding only one rail effects a saving of \$16 000, in favor of the alternating-current system.

A very liberal allowance has been made by placing the cost of the alternating-current motor equipments one-third in excess of that of the direct-current motor equipments; this, as above noted, is the present cost of the alternating-current equipment, and without doubt in the near future this difference will be greatly reduced.

The total investment for the direct-current system under the assumed conditions is \$490 100, while that of the alternating-current system is \$371 600. Reducing this to the cost per mile, it is found that the electrical equipment complete amounts to \$8168 for the direct-current system, and \$6193 for the alternating-current system, or a saving of \$1955 per mile in favor of the alternating-current system. Expressed in percentage, this means that the alternating-current system effects a saving of 25% of the cost of the direct-current system; in

other words, the cost of the direct-current system is 32% more than the cost of the alternating-current system, a showing

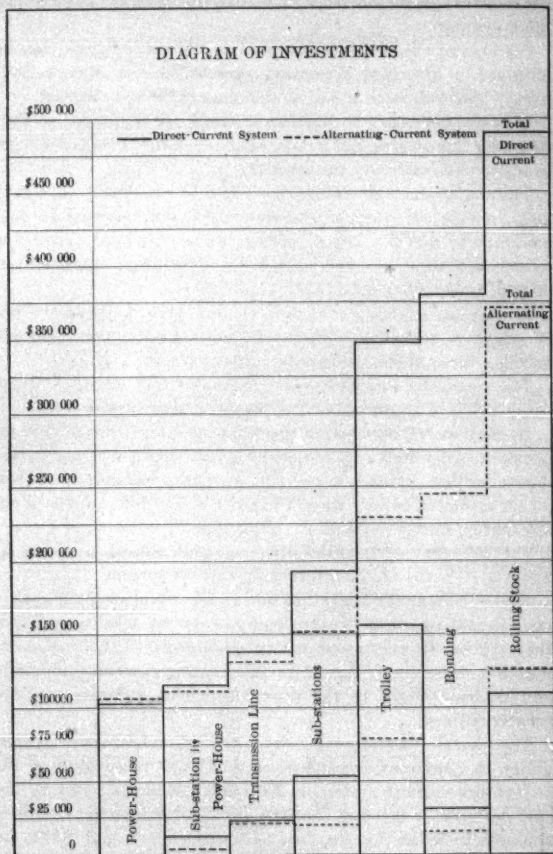


FIG. 11.

most favorable for the latter, and this indeed during the first year that this apparatus has been on the market.

With the alternating-current motor thus far perfected and

the large number of propositions whose realization is conditioned by a cheaper electrical equipment, it looks as if the alternating-current system would be very widely adopted.

ESTIMATED COST OF THE ELECTRICAL EQUIPMENT OF A
60-MILE SINGLE TRACK INTERURBAN RAILWAY.

POWER-HOUSE.	<i>Direct- Current System.</i>	<i>Alternating- Current System.</i>
Building.....	\$10 000	\$10 000
Foundations.....	2 500	2 500
Boilers and settings.....	12 000	12 000
Steam piping and covering.....	7 500	7 500
Engines.....	22 000	22 000
Generators: two 400-kw.....	18 000	23 000
Exciters.....	1 000	1 000
Step-up transformers, 800-kw.....	8 000	7 500
Switchboard.....	3 500	3 000
Wiring.....	3 000	2 500
Feed-water heater.....	800	800
Pumps.....	800	800
Coal storage.....	1 000	1 000
Smoke-stack and flues.....	2 000	2 000
Fuel economizers.....	3 000	3 000
Stokers.....	3 500	3 500
Incidentals.....	4 400	4 400
Totals.....	\$103 000	\$106 500
SUB-STATION IN POWER-HOUSE.	<i>Direct- Current.</i>	<i>Alternating- Current.</i>
Building extension.....	\$1 000	\$600
Synchronous converter, 300-kw.....	4 800	
Transformer, 300-kw.; 200-kw. alternating cur- rent.....	3 200	2 000
Switchboard.....	2 000	1 300
Wiring.....	1 000	500
Incidentals.....	600	200
Total.....	\$12 600	\$4 600
48-MILE TRANSMISSION LINE.	<i>Direct- Current.</i>	<i>Alternating- Current.</i>
Poles charged to trolley line.....		
Copper.....	\$10 000	\$11 500
Insulators, pins and cross-arms.....	7 500	5 000
Erection.....	4 000	3 000
Incidentals.....	1 000	1 000
Total.....	\$22 500	\$20 500
SUB-STATION ALONG THE ROAD.	<i>Direct- Current.</i>	<i>Alternating- Current.</i>
Building.....	\$2 000	\$1 000
Synchronous converter.....	4 800	
Step-down transformers.....	3 200	2 000
Switchboard.....	2 000	1 300
Wiring.....	1 000	500
Incidentals.....	500	200
Total.....	\$13 500	\$5 000
4 sub-stations.....	\$54 000	\$20 000

TROLLEY-LINE AND FEEDERS		Direct- Current System.	Alternating- Current System.
Poles, 3500.....		\$17 500	\$17 500
Poles distributed and set.....		4 000	4 000
Guys and anchors.....		2 000	2 000
Brackets with hangers.....		18 000	25 000
Copper, direct current:			
Feeder 12 miles, 500 000 cir. mils.....			
" 48 " No. 0000.....			
Trolley, 120 " No. 000.....		95 000	
Alternating current:			
Trolley, 60 miles, No. 00.....			21 500
Feeder insulators.....		2 000	
Erection.....		10 000	4 000
Incidentals.....		7 500	4 000
Total.....		\$156 000	\$78 000
BONDING OF RAILS.		Direct- Current.	Alternating- Current.
Both rails bonded.....		\$30 000	
One rail bonded.....			\$15 000
Cross bonds.....		2 000	1 000
Total.....		\$32 000	\$16 000
ROLLING STOCK.		Direct- Current.	Alternating- Current.
10 vestibuled passenger-cars, each equipped with 4 motors, and weighing about 30 tons..		\$75 000	\$85 000
2 express passenger-cars, equipped with 4 motors and weighing about 35 tons.....		18 000	20 500
2 Baggage-cars, each equipped with 4 motors and weighing about 30 tons.....		10 000	12 000
Snow-plow and construction-car.....		7 000	8 500
Total.....		\$110 000	\$126 000
RECAPITULATION.		Direct- Current.	Alternating- Current.
Power-house.....		\$103 000	\$106 500
Sub-station in power-house.....		12 600	4 600
Transmission line.....		22 500	20 500
Sub-stations.....		54 000	20 000
Trolley-line and feeders.....		156 000	78 000
Bonding.....		32 000	16 000
Rolling stock.....		110 000	126 000
Total.....		\$490 100	\$371 600
Cost per mile, direct-current system.....	\$490 100/60 =	\$8 168	
" " alternating-current system.....	371 600/60 =		6 193
Saving per mile, alternating-current system....		\$1 955	
The decrease of alternating-current cost in terms of direct-current invest- ment, 25%.			
The increase of direct-current cost in terms of alternating-current invest- ment, 32%.			

THE MECHANICAL CONSTRUCTION OF REVOLVING-FIELD ALTERNATORS.

BY DAVID B. RUSHMORE.

INTRODUCTION.

The mechanical design of alternators is undergoing rapid evolution. Among the first commercial machines in this country were the generators with stationary fields of cast iron, the yoke and poles being cast together. The armature had a smooth core and carried surface-wound wire in the form known as the "pancake" coil. The common frequencies were from 125 to 133 cycles per sec., and outputs ranged from 25 to 200 kilowatts; all the machines were belted.

On account of the small amount of wire carried, these machines had excellent regulation; the flat coil gave a nearly perfect sine wave. The single-phase reaction—for polyphase currents were not then in general use—caused the solid poles to heat and the relatively large number of poles of uneconomical section, together with the large mechanical clearances, made the machines heavy and costly. The armatures were hand-wound and the windings were often entirely destroyed by striking the pole-pieces, due to wear of bearings; or by a piece of metal falling on the armature.

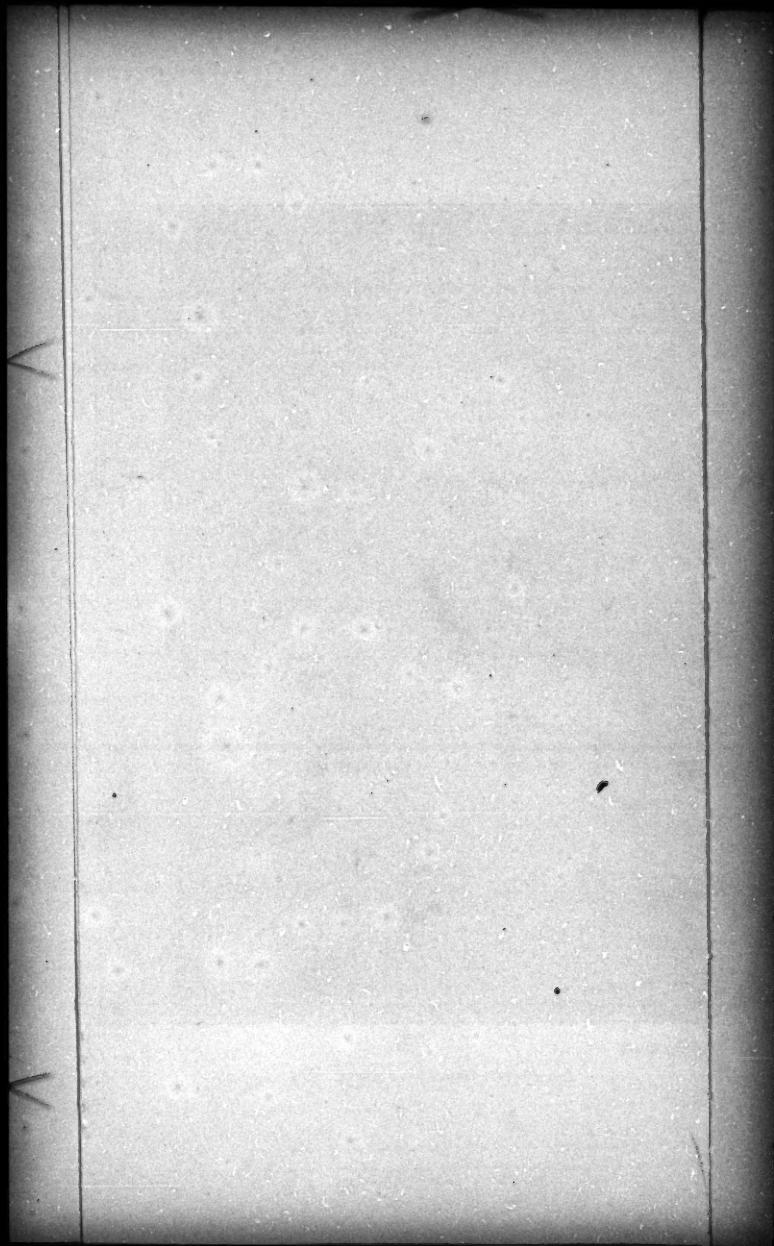
The next step was to laminate the poles and to cast them into the yoke; the armature was made iron-clad, with one large tooth per pole and the machine-wound coils were drawn up under the projecting tooth-face and held in place by wooden wedges between the coils in the same slot. Mechanically, this machine was a great improvement; the regulation and wave-form suffered greatly and soon the armature was changed to a many-slot distributed winding; at about the time when the use of polyphase currents was becoming general. With various small modifica-

tions this machine was standard for some time, until higher pressures and increased outputs made it desirable to revolve the field instead of the armature. Increasing sizes brought about the development of the "engine-type" generator, in which the revolving field was mounted on the engine-shaft, and for the past few years this has been the standard type in this country.

Generators driven by water-wheels have always been special, when direct-connected units have been used; the alternator is designed to suit the speed of the water-wheel, which in turn is determined by the type of wheel, the outputs and the head of water.

The indications are that the greatest development of the alternator driven by the steam-engine has been reached and that in the immediate future such units will be driven by steam-turbines and to some extent by gas-engines. It seems proper at this time to bring together in one place illustrations of present practice in the mechanical construction of engine-driven, revolving-field alternators, together with the development which has already taken place in turbine-driven sets. There is, to the writer's knowledge, no place where such information can be found; much of that given here has never before been published, and descriptions of foreign machines are scattered among so many sources as hardly to be available for American engineers and students. Discussion of the inductor alternator, except for a few minor details, has purposely been omitted. A special description of this excellent machine will be given later elsewhere. With this exception, the intention has been to illustrate modern practice as completely as possible, without including curiosities. Electrical and mechanical design are so closely related that a discussion of one necessarily involves the other; commercial designing involves such broad considerations of all factors of labor and material, as well as technical electrical points, that mechanical considerations, instead of following the electrical calculations, must now often precede them.

The prices of material and the cost of labor vary at different times and in different countries. The best designs of machines must, therefore, vary. The same specification can often be met by two radically different generators. Commercial considerations often limit designs, especially from the point of utilization of standard frames and parts. The factors of output, frequency phases, pressure, regulation, heating, and efficiency are so closely related, that if one or more of these be fixed, the others can be varied only within limits. As all losses result in heat, which must



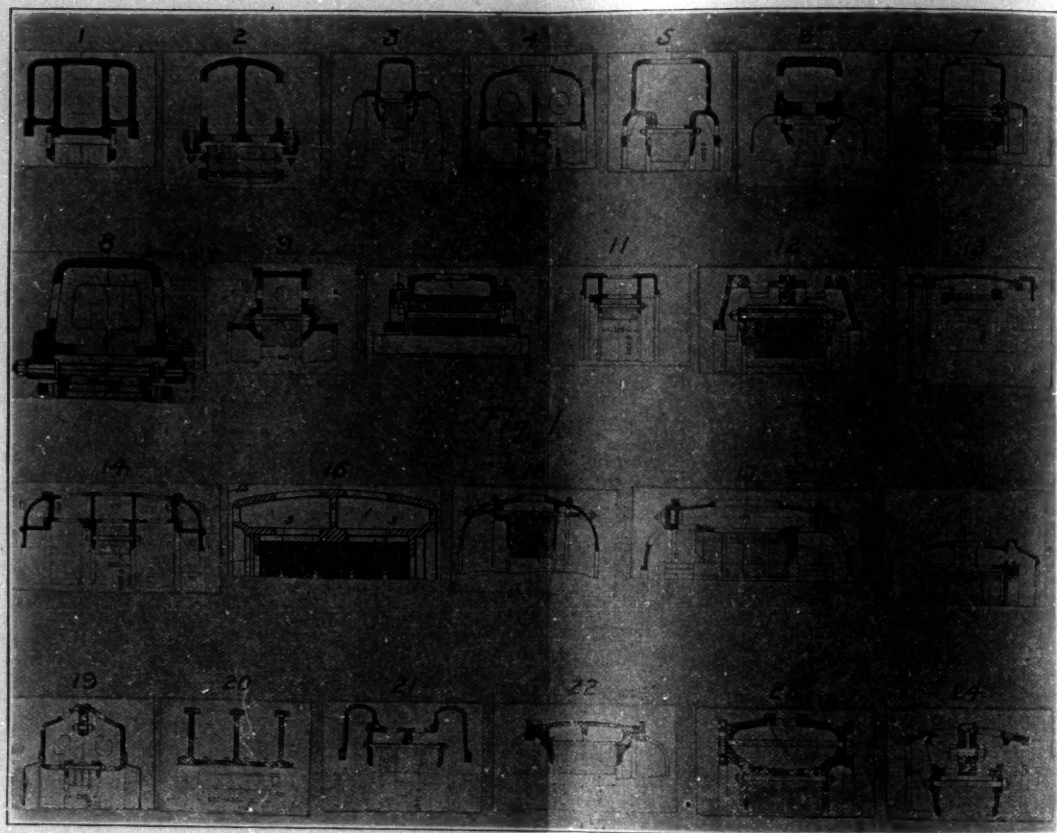


FIG. 1. Yoke-Sections.

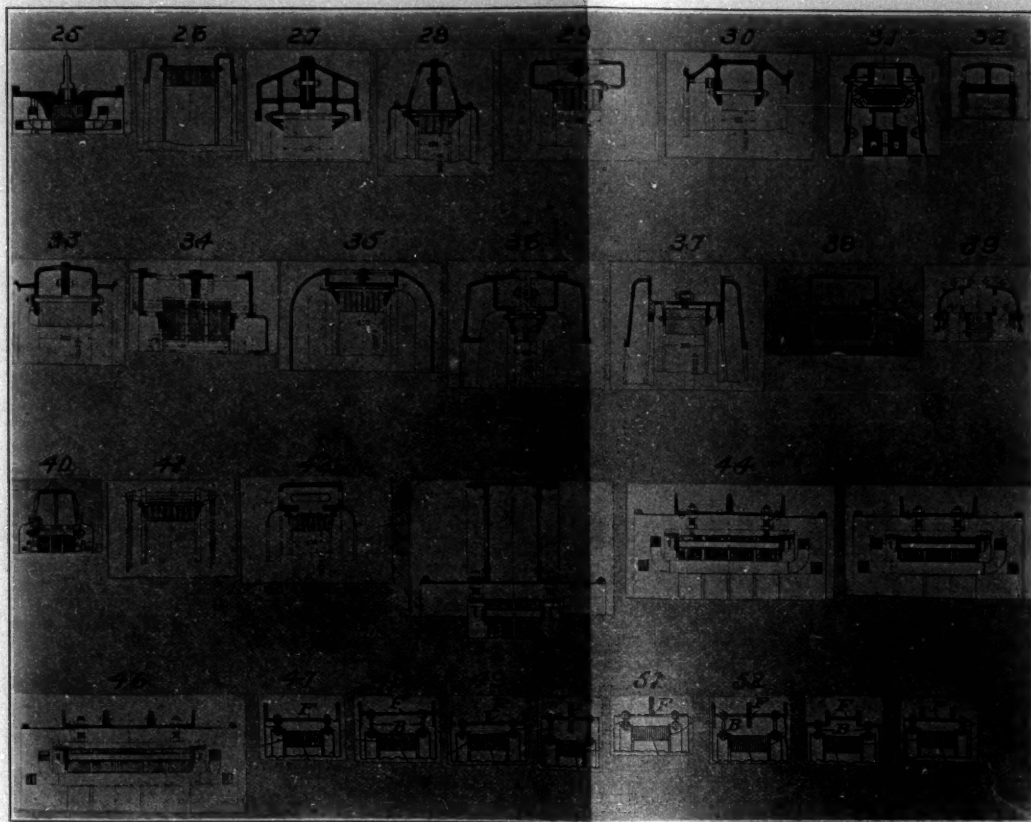


FIG. 2. Yoke-Sections.

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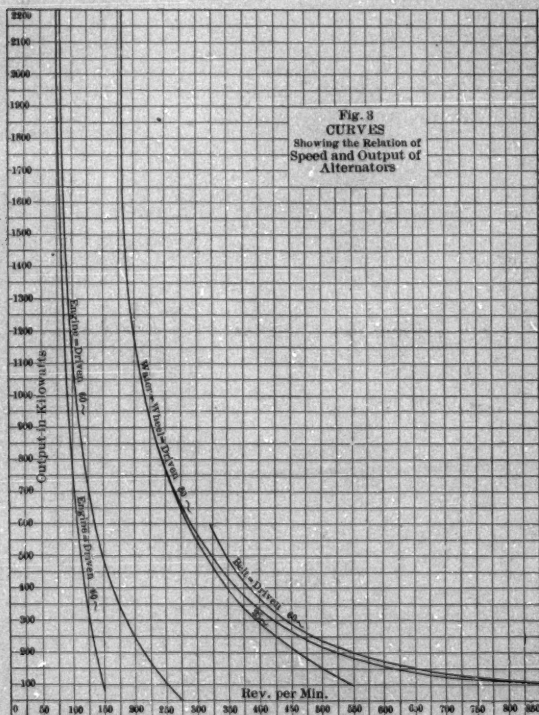
be radiated from a surface determined in part by magnetic considerations, the questions of heating and efficiency are closely related. The smallest gap being fixed by mechanical reasons, there is a minimum value to the kilowatts per pole which can be economically used. If other factors remain constant, we cannot save in weight of active material by increasing the speed of revolution unless we, at the same time, increase the peripheral velocity, which may not be possible. To some extent regulation and efficiency are incompatible; cheap electrical designs may necessitate expensive mechanical features. These are but a few of the items which indicate how broad a view must be taken in designing alternators. In most machines of to-day, it is usual to work out a preliminary electrical design; the mechanical features are then developed, and the necessary modifications are then made in the original calculations.

YOKES.

The yoke or armature frame is one of the most important mechanical parts of the engine-driven alternator. Its object is to support rigidly the armature laminations and winding while affording good ventilation and giving an artistic appearance to the machine as a whole. The commercial object of course is to attain this end with a minimum of labor and material; to this end a large number of different designs have been made, some of which are shown in Figs. 1 and 2. For the past decade the output of single units has increased rapidly, while the speed for large sizes has remained fixed at 75 rev. per min. The outside diameter has thus increased constantly and with it the difficulty of proper yoke-design, without excessive weight. Probably the maximum diameter has already been reached, for with the introduction of turbine-driven alternators, the sizes of machines for the same output are very much reduced. The speeds of various types of alternators are shown in Figs. 3 and 4.

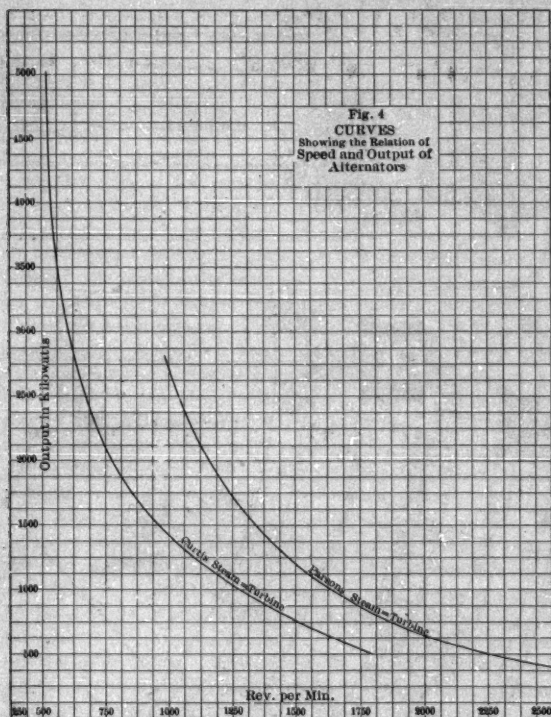
While there are many different yoke-sections, there are but few different types; first, there is the cast-iron box-section, in which the frame is divided horizontally, forming a beam or arch supported at each end, uniformly loaded; the greatest moment of inertia, with the least weight, is aimed at; the outside of the shell is well rounded to give a finished appearance. The expensive patterns formerly necessary are now dispensed with by "sweeping-up" the mould. Air-gaps or mechanical clearances vary from 0.125 in. to 0.75 in. in engine-driven machines, hence any appreciable

deflection of the yoke would be inadmissible. The deflection of the yoke is due to its own weight as well as to that of the laminations, winding, etc.; in order to provide for wear in the bearings it is usual to set the revolving field high, which brings an additional stress on the yoke, due to the unequal magnetic pull.



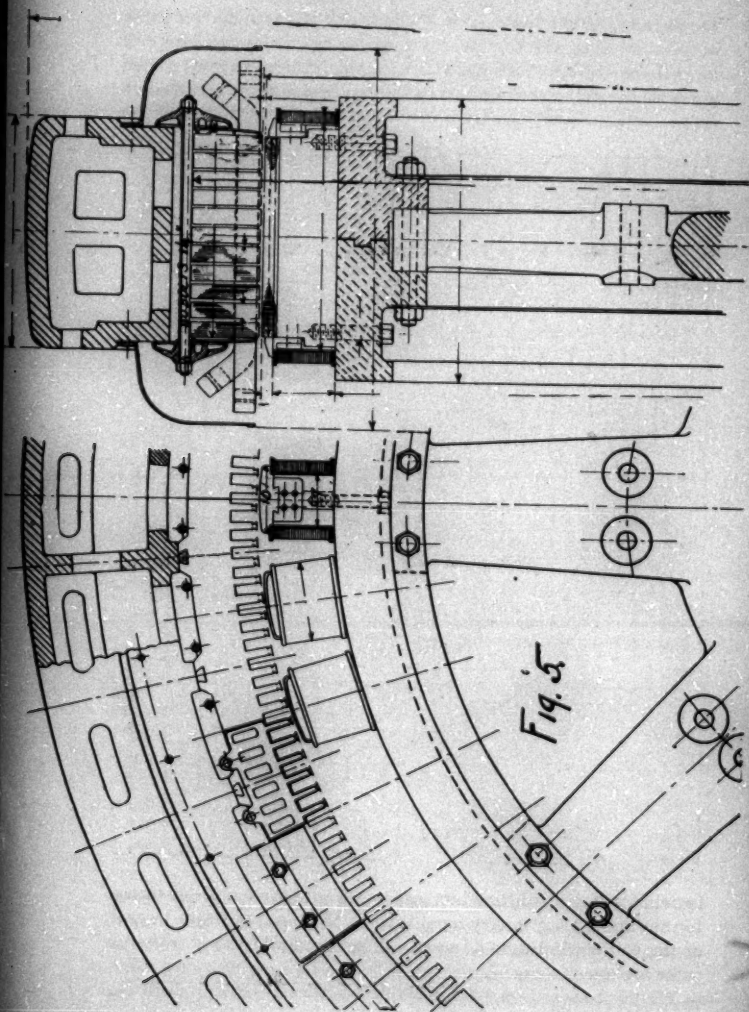
Large boring machines are usually horizontal, so it is apparent that the greatest care must be used in machining the frame in order to allow for the deflection which will be found under conditions of service. With this style of yoke, the feet on which the frame rest are sometimes given a pressure toward

the centre and the lower part of the frame is supported by jacks at one or more places. If alternate layers of laminations are lapped and strongly clamped together, the friction between plates gives them a resistance against deflection, which may be considerable; if the laminations are firmly dove-tailed into the yoke, the



resistance is still further increased. It is customary to arrange for sliding the stationary armature on the base, in order to gain access to the windings and poles. The standard form of cast-iron yoke is shown in Fig. 5.

Where the cast-iron yoke is divided vertically, each half of the



frame is constructed as a cantilever, growing smaller in section toward the top. With this construction, in which the machine is supported at the bottom, more difficulty is experienced in preventing vibration; there is here no base for yoke and bearings, which are supported on independent foundations. Access to the winding is had by sliding the armature back from the shaft. When it is desirable to do so, for reasons of transportation or otherwise, the frame may be sub-divided into more than two parts.

In some cast-iron box-sections such as are shown in Nos. 26, 27, 28, 29, 33, 34, etc., the frame is divided by a plane perpendicular to the shaft. The clamps for the laminations are cast on the frame and the active iron is held by bolting together these parts.

Another type of box sectional construction, illustrated in No. 35, has been used by Brown Boveri & Co. The frame is light and is supported mainly by flanged arms, which join all parts of the circumference to a ring supported on a trunion surrounding the bearing. In place of the usual foot there is a screw for preventing rotation of the armature, and when this is removed the whole frame may be revolved upon the trunnion bearings. This design gives a light yoke-section, and thus a light machine; the armature is difficult of access on account of the number of arms, and it is not easy to provide for wear in the bearings. When properly erected this construction should be very firm. In some cases instead of channel-arms, rods have been used, but they are liable to vibration, if long. The construction of this type is illustrated in Fig. 6.

A large variety of box and shell cast-iron sections are possible, as shown. These vary in minor details, but all perform the same general functions. A modification of the box-section is that in which a small box is stiffened by wide rings, which are made removable; one ring may be cast with the box-section. Yoke No. 41, illustrates a distinct type, shown more clearly in general construction in Fig. 7. In this, the non-active metal is reduced to a minimum. The frame is braced by two sets of tie-rods, forming chords, which connect to rods passing through or just back of the laminations; instead of the box-frame we have a single cast ring on each side of the active iron; it is claimed that in large machines the weight of the frame can be made less than one-fifteenth that of the box construction. A modification of this type is to make tangents of the tie-rods instead of chords; the ends of these rods are

fastened to pivoted arms in the vertical plant of the laminations; the rods are drawn up when cold and as the machine heats the desired stress is brought upon them. These constructions, which are the inventions of Mr. Lasche of the Allgemeine Elektricitäts Gesellschaft of Germany, offer many advantages from a manufacturer's point of view. With the exception of the end-rings, which may easily be kept in stock for different diameters—the

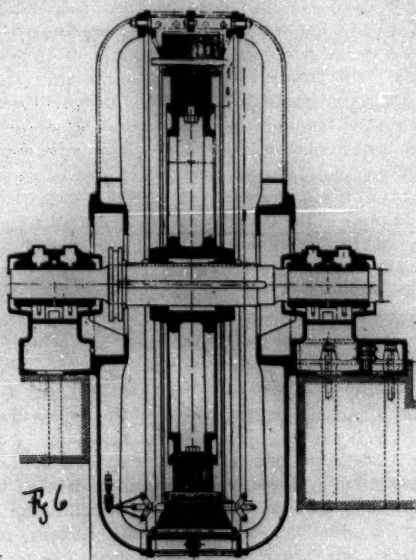


FIG. 6. Frame of Brown, Boveri & Co.

remainder of the material is easily adapted from supplies which may be kept on hand, and machines of any diameter or practical length may be quickly manufactured, as the long waits incident to pattern shop and foundry work are eliminated. The laminated iron is well exposed to the air and the ventilation is excellent which should, where the larger part of the heating is due to iron loss, result in a better utilization of material. The light construction would be liable to vibrate with large diameters, and the rough

appearance has been the subject of criticism, as well as the lack of protection to the winding.

A third distinct type is shown in yoke-section No. 43, various modifications of which follow. In this the supporting section,

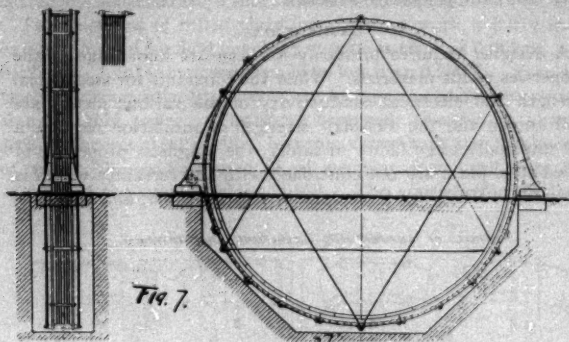


FIG. 7. Braced Tie-Rod Construction.

instead of being a cast ring, is constructed of rolled plate and angle-iron. The laminated iron is built up separately and is then placed in the casing and held in position by bolts. This is shown clearly in Fig. 8. Yoke sections No. 43 to 54 show differ-

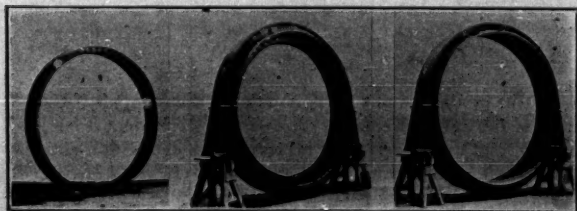


FIG. 8. Rolled Plate Box-Yoke.

ent frames built up in this general manner. The strength of the supporting structure is obtained with light weight and a minimum material; the electrical part is well protected and it is not necessary to bore out the frame as with the cast construction. The ventilation may be made good, and the appearance is pleasing. In this construction a considerable amount of labor is required in

bending and fastening the plates and angle pieces composing the frame. While the cost of material may be small, the cost of labor will be high. There is at present no construction more satisfactory for large machines than the cast-iron yoke of box-section with laminations held by dovetails.

LAMINATIONS.

A designer requires primarily an accurate knowledge of the properties of his materials. While the constants for mechanical strength and electrical conductivity of the various metals are well known and the dielectric strength of insulation requires a not unusually large factor of safety, the magnetic properties of rolled-steel plate are not controlled with the certainty which is desirable. Much has been done in this direction, and the solu-

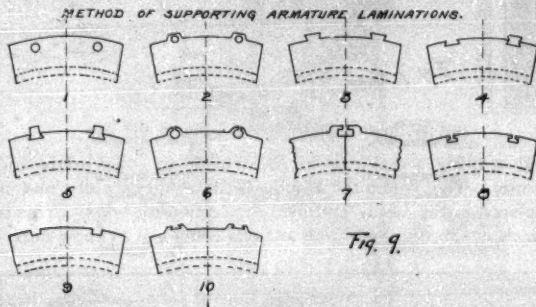
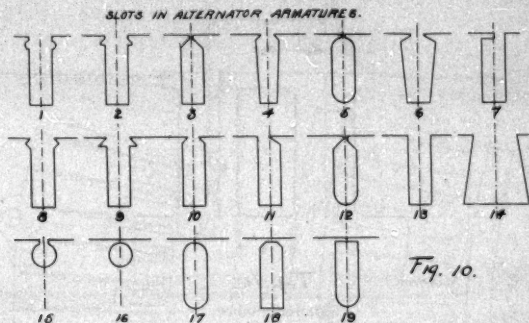


FIG. 9.

tion of this problem is now being sought by many minds. Guarantees of heating and efficiency are largely dependent upon the iron-loss, and any uncertainty regarding this demands a greater margin than otherwise would be necessary. In the tests which are always made before iron is used, the results may vary less than five per cent for a considerable time, when some iron may be received with several times allowable loss, which, so far as is known, has received the usual treatment. The hysteresis loss may increase with time, an effect called ageing; to prevent this certain chemical composition and treatment is necessary. In order to reduce this loss, iron must be annealed at a high temperature after rolling; this is sometimes done after punching and sometimes before; if done after punching, the shape of the plate

may change, and filing of the slots may be necessary to a considerable extent; when annealed before punching, difficulty may be experienced in working with a soft metal which drags on the edge of the die, especially with thick plates, and the lamination is thereby hardened for a short distance on the edge.

The thickness of rolled plate for armature work is 0.014 in., or 0.018 in., and for field punching may be as thick as 0.062 in., or 0.125 in. A cubic inch weighs a little less than 0.280 lb. Insulation separating adjacent sheets may be japan, a silicate preparation, or thin paper. The space occupied thereby is about 10% of the apparent section, but this varies with the thickness of plate; the section used is of peculiar form and from 20 to 60% of the original sheet is lost. The construction of dies



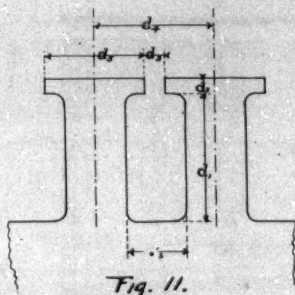
necessitates that the length of lamination should not be much greater than 24 in., and complete form may be punched out at once, or by using blanking and slotting dies, in several operations.

Wrought iron has been almost entirely superseded by steel for armature plates; the steel is made by the open-hearth process, either acid or basic, and limits are set to the allowable percentages of carbon, manganese, sulphur, phosphorus, and silicon which may be present. The combined iron-loss per pound for a certain thickness of sheet at given frequency and density is limited, and also the percentage increase of this loss under continued heating at a fixed temperature for one month.

SUPPORTS FOR LAMINATIONS.

If the alternate layers are lapped and the clamps drawn to—

gether with a strong pressure, the laminated ring will be self-sustaining. It is, however, necessary to support the active iron from the yoke by one of a number of possible methods; those in common use are illustrated in Fig. 9. The laminations may be supported on bolts or rods, the ends of which are held by the frame. Nos. 1, 2, and 6 show variations of this kind of support, first where the rod passes through the active section, second, where the laminations project back for the bolt-hole, and a modification in No. 6 which prevents the active flux from cutting the bolt. This manner of supporting the iron is economical and satisfactory on machines of certain dimensions. If the density in the armature core is high, No. 1 should not be used; with a considerable length of armature core and especially with much



Slot Inductance.

radial depth of iron, the surface of the core may bulge or the size of the bolts to prevent it may become excessive. Insulated bolts may be used but as a rule are undesirable from a mechanical standpoint.

No. 3 is a very satisfactory method for use with a cast-iron yoke. Dove-tails are cut in the frame, parallel to the shaft, and into these corresponding projections on the laminations are fitted; this makes an absolutely reliable method of retention; somewhat expensive but suitable for the largest machines. Instead of the preceding, a key may be screwed to the frame as in No. 4, which gives results similar to the dove-tail and offers several constructional advantages.

No. 5 shows a method where the key-seat in the frame is straight and the key used only for alignment. A driving fit

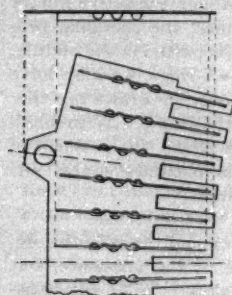
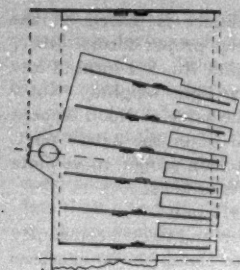


Fig. 11.

FIG. 12. Ventilating Space-Blocks.

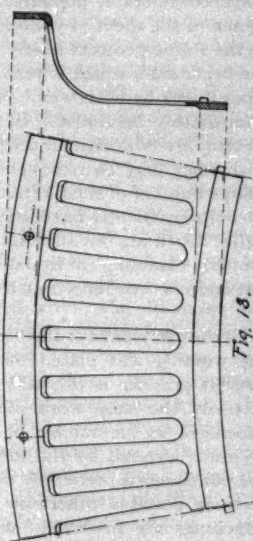
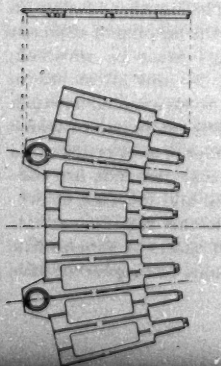


Fig. 13.

FIG. 13. Shield for Protecting Armature Coils.

holds the key to the frame, while reliance is placed on the friction between plates and keys to keep proper form. No. 7 shows a peculiar method used abroad, and No. 8 a form of key used on small machines and for holding light weights. No. 9 is simply an aligning key, and No. 10 the same as No. 4, except that the key is in a projection instead of in the active part. Where the support is back of the core-section proper, more plate is required but less loss occurs in the bolts or keys.

CLAMPS FOR LAMINATIONS.

In order to prevent humming of the iron and to give continuity to the magnetic circuit, it is necessary to clamp the laminations under considerable pressure. Methods for doing this are clearly shown in the sheet of yoke-sections; in most machines, one side of the frame projects nearly to the inside armature surface, and the other side, which is removable, is drawn tightly against the laminations by bolts which pass either through the active iron or immediately behind it. In some machines, the clamping projections are both cast on the frame which is parted in the middle; both rings may be removable. Instead of rings, we may have a large number of small retainers which are either drawn together by bolts or each is fastened directly to the frame. With small radial depth and small length over laminations, the problem of properly clamping the iron is simple, but in machines of large output and low frequency much care is required.

SLOTS.

In the early days of the "pancake" coil and the smooth core, the winding was placed on the surface of the armature, but present practice is to place all coils in slots. To do this satisfactorily the shop work must be carefully done. The die is expensive, as the number of slots is increased, and the cost may be much affected by the form of slot. The number of slots in the punchings is preferably even, to make the lapping of adjacent sections possible otherwise the punchings must be reversed; punchings are preferably made between 24 and 36 inches in length for large machines; filing of slots is to be avoided as much as possible, hence an additional allowance is made in slot-width which becomes more important as the number of slots is increased and their dimensions diminished. Electrical demands are conflicting; economical utilization of material and low cost of production demand few and large slots, while the requirements of heating and regulation call for many small ones. A general rule of electrical design is to avoid concentrations of magnetomotive

forces and of sources of heat, while opposed to this, are the best condition for manufacture; hence the result therefore is always a compromise. Where the slots are large and wide, and especially if the teeth are narrow, the reluctance of the path of magnet flux varies, introducing harmonics into the e.m.f. wave, and causing vibration of the teeth; this, in certain cases, has broken them off. A sharp corner to the pole-piece accentuates the trouble; with solid pole-faces, the ratio of gap-length to slot-width must not be less than a certain figure, or undue losses and heating will occur in the pole-shoes; under the same condition, copper damping devices cannot be used close to the armature.

Slots may be punched in the armature at the same time that the lamination section is punched from the sheet; the lamination may first be blanked out and the slots punched one or more at a time on a special machine, or the plates may be built up into the armature ring and the slots formed with a milling cutter. The first and second are in use in this country, and the choice depends upon whether the number of plates to be punched will pay in the saving of labor for the greater cost of a complete die. The first method gives the best results; the second is apt to require more filing; the third method is foreign but is open to criticism because of the increased iron-loss which must result therefrom. It was used in the early days of railway-motor work, but has long since been abandoned here. Some of the machines at the recent Paris Exposition were slotted in this way. Fig. 10 shows most of the forms of slots in use at the present time in alternating-current machines; they may be divided into three classes: Open slots, partially-closed slots, and closed slots. The advantages and disadvantages of each are partly mechanical and partly electrical; open slots permit the use of machine-wound coils, which may be entirely insulated before being placed in position, a thin paper slot-insulation being used for mechanical protection. The insulation may be continuous; the filing of the slots need not be excessive. Coils are easily placed in slots or removed in case of accident and the self-induction of the slot is less. In certain cases small harmonics may be introduced into the wave-form, the excitation is greater for the same gap or we have a smaller clearance for the same excitation. Foucault losses may be produced in the pole-shoe or damping devices. Open slots are shown in Nos. 1, 2, 8, 9, 13, and 14. Partially-closed slots are of two kinds, those which may be wound through the opening and those wound from the end. Slots 7, 10, and 11

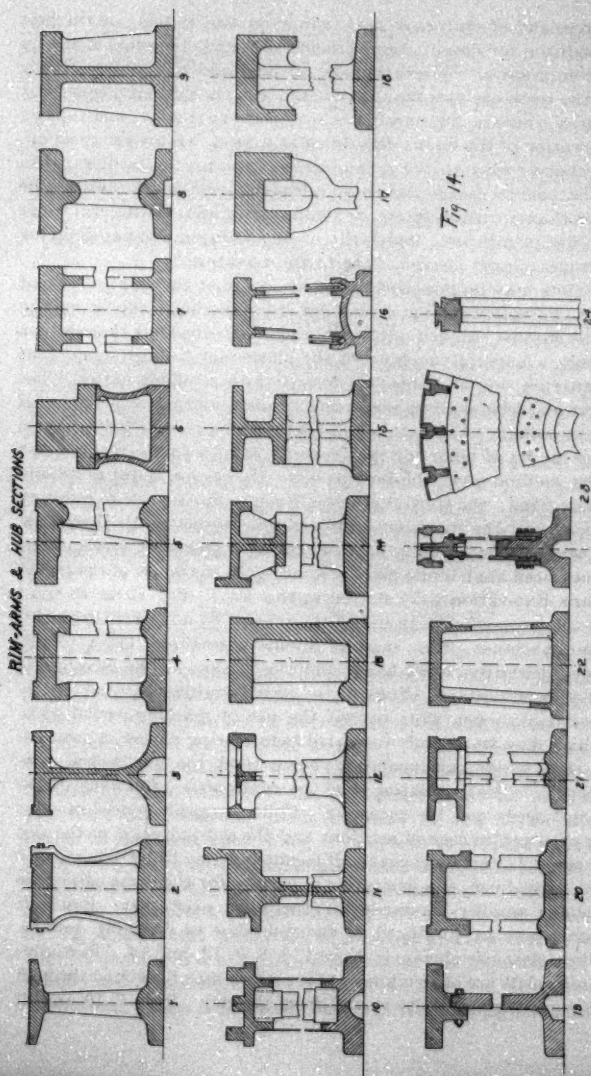


FIG. 14. Rim-Arms and Hub-Sections.

may be wound from the surface while such forms as 3, 5, 12, and 15 must be wound from the end. Where such slots are wound from the surface, a wedge is used and held in place by the projecting corners. Partially-closed slots require greater care in construction and render the problem of insulation more difficult than open slots. They decrease the gap-reluctance and the foucault loss in the pole-face while increasing the self-induction of the winding. The magnetic flux undergoes less variation and the clearance may be greater. Slot 10 may be wound from the surface where a heavy slot insulation is used sufficient to fill up the distance over which the corner projects. Slots 7 and 11 may be surface wound with two conductors, having a depth equal to that of the useful part of the slot, or with four coils or conductors per slot.

Where closed slots are used, it may be assumed that labor is cheap and that wholesale manufacturing is not in vogue. The slots must be carefully filed if the space is well utilized; the insulation as well as the winding must be introduced from the end; in long cores, this is difficult, especially where there are many turns per coil. In some cases with closed or partially closed slots and a many-turn coil the latter is machine-wound and then cut, straightened, threaded through the slot and every turn separately soldered. With closed slots, the regulation is worse, and for standard guarantees the machine becomes very heavy. There appear to be no compensating advantages for this form of slot.

The closed and partially-closed slots prevent foucault losses in solid conductors; with open slots the bottom conductor may be made solid and the top one of cable if necessary to prevent foucault losses.

To illustrate the importance of slot-shape on inductance and consequently on regulation, Fig. 11, showing a partially-closed slot is given. The inductance varies with the magnetic permeance (λ), where

$$\lambda = \text{Constant} \left\{ \frac{d_1}{3 \omega_s} + \frac{d_2}{d_1} + \frac{2 d_3}{\pi d_1} \right\} \times \text{length of iron core.}$$

Where the slot is round or where the corners are formed by quadrants of considerable radius, there is much less danger of insulation rupture due to the sharp bend.

ARMATURE WINDING.

The conductor used for alternator armature winding may be round or square copper wire, rectangular strip, or stranded cable. The cost of the generator is largely dependent upon the proportion of the slot cross-section which is occupied by active copper. There is a practical limit to the size of strip which may be used in the top of the slot and above which stranded cable is necessary. Cable has an effective section slightly over three-fourths of the apparent area, but with its use much less heating may result from the increased resistance loss than would come from the foucault currents induced in a solid conductor of the same apparent section. After manufacture, cable is round but must be rectangular before it can be used, and must come very closely to gauge without being hardened in the process.

Where cable is used it is customary to give the coil a vacuum treatment which thoroughly impregnates all the interstices with an insulating compound. This removes all moisture and makes the coil solid and firm while entirely eliminating foucault losses. In some cases a solid conductor is used in the bottom of the slot and cable at the top.

Insulation is almost entirely an electrical problem, but one of the greatest dangers to which it is exposed is from vibration of the coil as a whole or of the individual conductors in the coil. For this reason, which explains the great advantage of the stationary over the revolving armature, the insulation should possess elastic properties. Coils must fit slots tightly and allowance must be made for a small decrease in size due to drying out under long-continued heating. With deep slots and narrow teeth the latter may vibrate slightly as each pole passes under them, and with very high-speed machines, especially those direct-connected to water-wheels, a certain vibration of the whole machine is inevitable. The end cross-connections must often be securely held for this cause as well as to protect against the bending action due to heavy short-circuits.

VENTILATING SPACE-BLOCKS.

Some years ago a radical improvement was made in dynamo design by the use of air-ducts in the armature core. This has since been a standard method of construction for all cores whose length exceeds 5 or 6 inches. As heating is one of the principal limitations to the output of an alternator, the relation between the losses and radiating surface is most important; in direct-current work it is sometimes used as a starting point for the

design. It is usual to allow for effective radiating surface at least one side of the exposed iron in the duct, so it is easily seen that the radiation from the armature may be increased by the introduction of ventilating spaces into the cores, which cause but slight increase in volume or weight of the machine.

It is desirable that consistently-designed machines reach their limits of temperature and regulation at the same time. The external dimensions of the core are largely determined by magnetic reasons and the proper choice of number and size of air-ducts is therefore the point which largely decides the armature heating. In very small machines, ventilating spaces have been made 0.156 in. wide; for most engine driven alternators a width of 0.312 in. to 0.375 in. is used; in large machines of great radial depth of lamination, 0.5 in., 0.75 in., and even 1 in. ducts have been used; two spaces each of 0.5 in. are, however, preferable to one space of twice the size. The best width depends upon the depth of laminated iron, the peripheral velocity of the revolving field and the type of space-block used. The distance between ducts in core varies from one to three inches. Small ducts at frequent intervals help to reduce Foucault losses; it is usual to place a space-block on each end of the core between the laminations and clamps.

The first space-blocks were made of brass or composition casting consisting of a solid flat plate with raised fingers on one side. The necessary thickness of the plate occupied half the distance between laminations and the blocks were expensive as well as inefficient. Fig. 12 illustrates some modern types; the first is a cast block such as it is desirable to use in certain cases, especially at the core ends; it is of skeleton form to give the least weight and to permit the greatest effective width of duct. The second type is the best construction; it is made entirely of steel; a plate $1/32$ in. of thickness, of same form of armature lamination, has supporting pieces punched in, as shown, which in turn support steel fingers so formed as to be securely held in place. This construction is very firm and gives the maximum effectiveness of ventilating space, and without the introduction of non-magnetic material. The third type shown has the same advantages as the second with regard to space; the upright fingers are supported in a different manner.

Where the poles are laminated and placed close together, it is sometimes found desirable to have ventilating ducts in the revolving field-frame opposite to those in the armature; in some

foreign machines, ducts in the one are staggered with respect to those in the other.

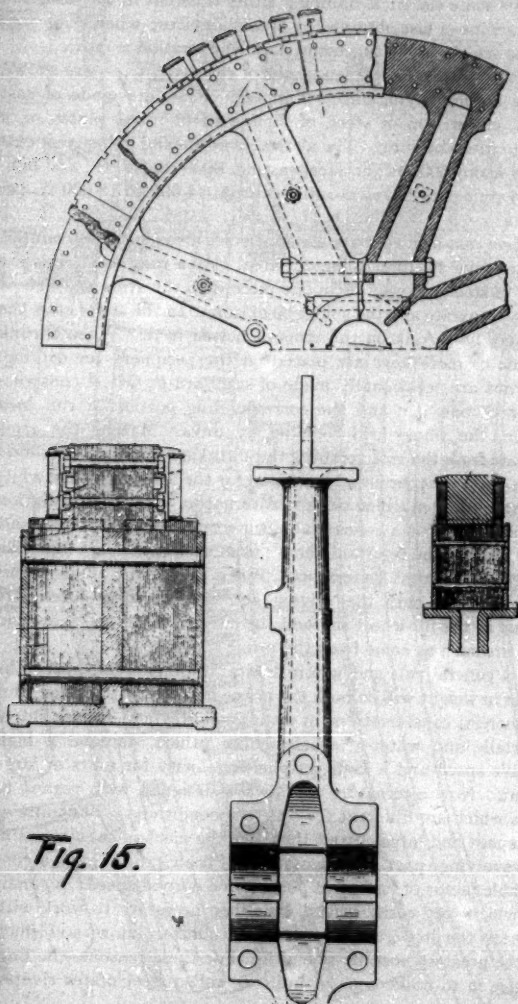
SHIELDS.

To give access to the armature winding it is usual to make the yoke-section so that all coil-ends and cross-connections are well exposed an essential consideration from the standpoint of ventilation. To protect the cross-connections from mechanical injury, shields are fastened to each side of the frame, projecting out and over the cross-connections. These shields are sometimes made in a continuous ring and support the yoke. Many variations in form are found, but a typical modern design is shown in Fig. 13. The light iron casting is well opened to give good ventilation and is of such length as to be easily handled in assembling or making repairs; a minimum of machine-work is required; projecting lugs on the inner ends engage with adjacent sections securing accurate alignment.

RIMS, ARMS, AND HUBS.

The fly-wheel is at times a part of the generator construction. At the higher frequencies the natural velocity of the revolving field approximates that which is used for fly-wheels and the two are often advantageously combined. At 25 cycles this does not give good results nor for direct-current generators, where frequency is much lower than 25 cycles. Fly-wheels are used for two purposes; *i.e.*, to give uniform angular velocity through one revolution and to give uniform speed over short periods of time. The usual specification is that the variation in angular velocity shall not exceed from 2.5 to 3 electrical degrees in one revolution; as the frequency and the number of poles is increased, the difference between the real and the electrical angle becomes greater, and the fly-wheel must be heavier.

With alternators the problem of the fly-wheel is almost entirely that of the requirements for parallel running; much has been written on this subject with but little of definite results. To give briefly the necessary relations, it may be said that in itself variation in angular velocity has but little to do with trouble in parallel running, except as it is related to other constants. The impulses from the piston give a frequency equal to the revolutions per second; the moment of inertia of the revolving part and the electrical constants of the machine give a natural period of oscillation; if these are equal we have the condition of resonance. It is necessary for successful work that they bear an approximately fixed relation to one another; it is also necessary

*Fig. 15.*

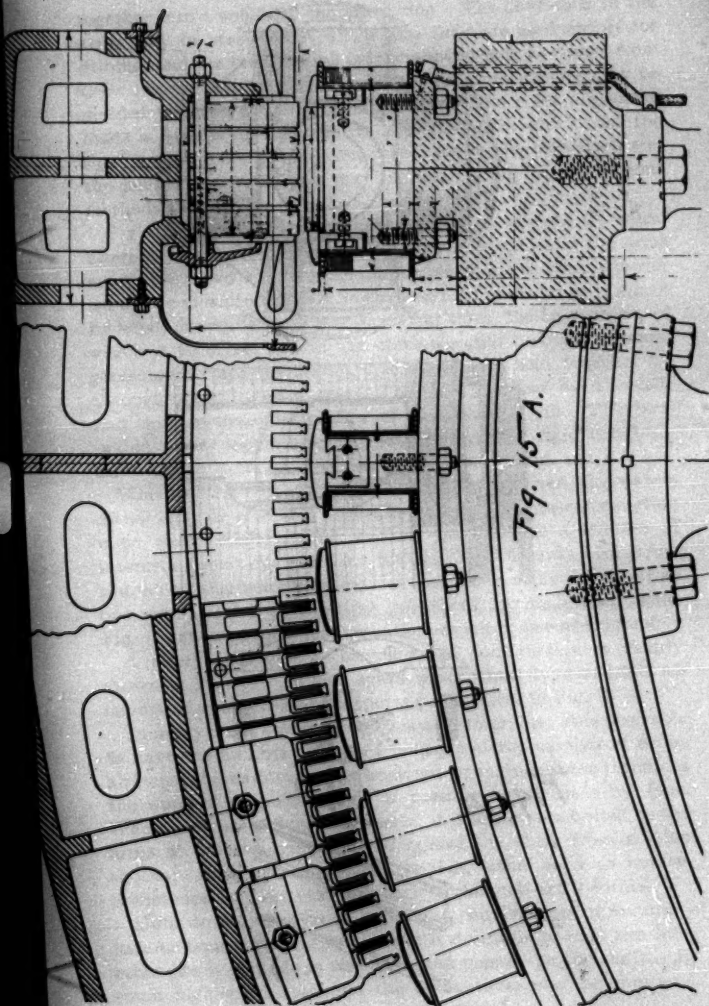
Fly-Wheel Type Revolving Field.

to have some electrical damping either inherent in the design of the machine or else obtained by special devices; when these conditions are observed, successful parallel operation is insured.

Sections of rims, arms, and hubs of revolving parts are shown in the accompanying sheet (Fig. 14). Rims are made of cast metal, either iron or steel, of laminated or rolled plates, or of combinations of both. The allowable peripheral velocity of cast iron is about 5000 ft., of steel-casting 8000–10 000 ft., and laminated rims may have velocities of from 14 000 to 18 000 ft. per minute.

Where cast-iron rims are used the poles are sometimes counter-sunk to give additional contact-area. As a rule, solid rims are made of steel and may be in one piece with the arms and hub or may be separate and the spider be of iron. In the latter case, the rim may be shrunk on the arms or bolted to it. When shrunk on, one or more keys are placed on the periphery for driving. The rims are occasionally made of standard fly-wheel construction with one arm and the corresponding portion of rim to a section, the whole held together by links. Making the arms separate from the rim, removes the shrinkage strains, and allows the use of a cheaper metal, cast iron for the arms and hub, while requiring more machine work. Alternators with bad regulation will often run for a considerable time on short-circuit without harm, so that the resultant shocks from such causes are less than with direct-current generators. When the field and fly-wheel are combined, both the driving and the retarding forces are located in the fly-wheel rim and the only stress in the arms and shaft are such as come from the prime mover.

As a general rule and within limits, the higher the speed the lighter in weight will be both the prime mover and the generator. Commercial considerations in some instances and the height of waterfalls and water-wheel design in others, demand a high rotative speed and a high peripheral velocity for units of large output. Now alternators are always designed with regard to limits which are different for different conditions. For units of high speed and large output these are the mechanical stresses in the revolving part. In most cases, these must have a considerable factor of safety at 50% above normal speed; a condition which may easily exist. It is then necessary to work with materials the properties of which are accurately known and which has the greatest possible strength. For these reasons, the best practice is to make rims of built up rolled-steel plates riveted



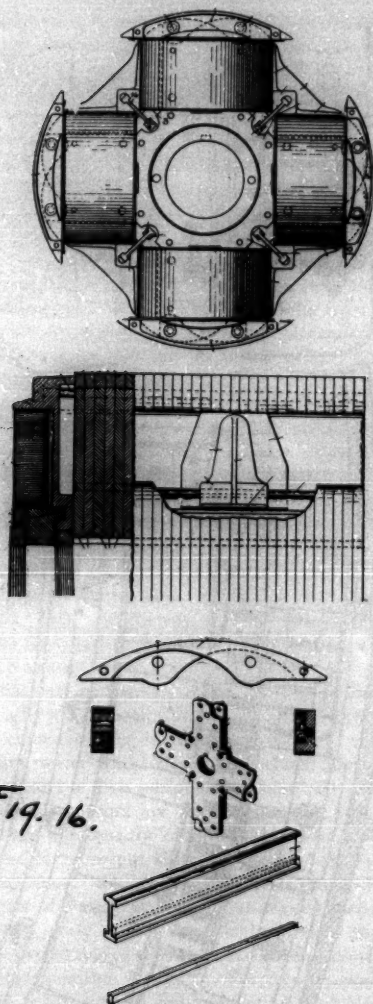


Fig. 16.

Turbine Alternator Constructor..

together into a solid self-contained ring. The dove-tails in the arms may be straight, in which case they are used simply for driving, and the only tension on the arms is such as comes from their own weight. In other cases, the resisting stresses may be divided between the arms and the rim. The poles are either made in one piece with the rim laminations, in which case the shoe, if there is one, is made removable and retains only itself and the field coils, or the pole may be held by any of the various methods shown.

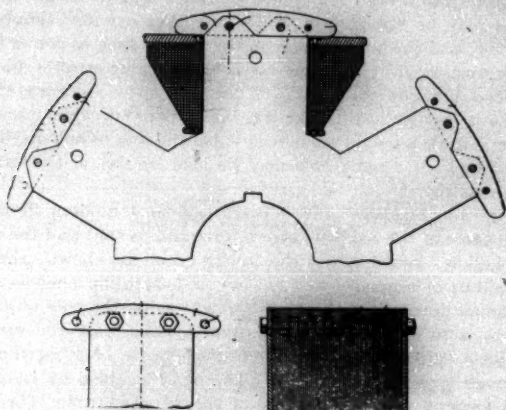
Fig. 15 illustrates the construction of a modern fly-wheel alternator of the "engine-type"; the hub is split and the arms are hollow; two different rim-constructions are shown; the rim is built up of laminated iron, in one case held to the inner cast iron by small dovetails with nearly straight sides, the only object of which is to drive, and in the other a radial cast-iron section, projects through the laminations, which are held together by through rivets in both cases. The poles are held by dovetails and keys on the outer surface of the fly-wheel rim. The laminated places lap in alternate layers, giving a rigid construction. A cast-steel construction is illustrated in Fig. 15a.

While high-speed water-wheel and turbine-driven alternators do not have fly-wheels in the ordinary sense, the rim-construction must be unusually strong, and for this purpose a number of interesting solutions have been found. Fig. 16 shows a construction for small machines where it is possible to make the rim from one sheet, and the projecting pole-shoes are made removable. Fig. 16a shows a modification of the preceding assembled field.

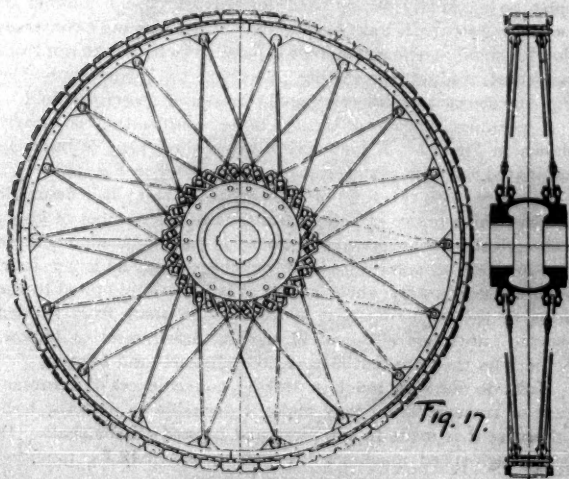
A peculiar tangential, bicycle-spoke construction is clearly shown in Fig. 17. A high-speed water-wheel type of built up laminated rim with plate supports is illustrated in Fig. 18.

In many cases two rows of arms are preferable; it is desirable to have the number of poles a multiple of the number of arms, although this cannot always be done; in engine-driven machines the number of poles should if possible be divisible by four. Where a separate fly-wheel is used, it is sometimes bolted to the arms of the revolving part to relieve the shaft from sudden shocks; arms are elliptical in section, either solid or hollow. Sometimes they are cast into various channel- and I-forms.

Hubs do not vary much in design; conveniences of manufacture or transportation may make it desirable to part the hub, otherwise it is made in one piece and pressed on the shaft. In small high-speed machines the laminations may be mounted

*Fig. 16A.*

High-Speed Revolving-Field Construction.

*Fig. 17.*

Bicycle-Spoke Construction.

directly on the shaft, in which case it is desirable to use at least two keys.

FIELD-COILS.

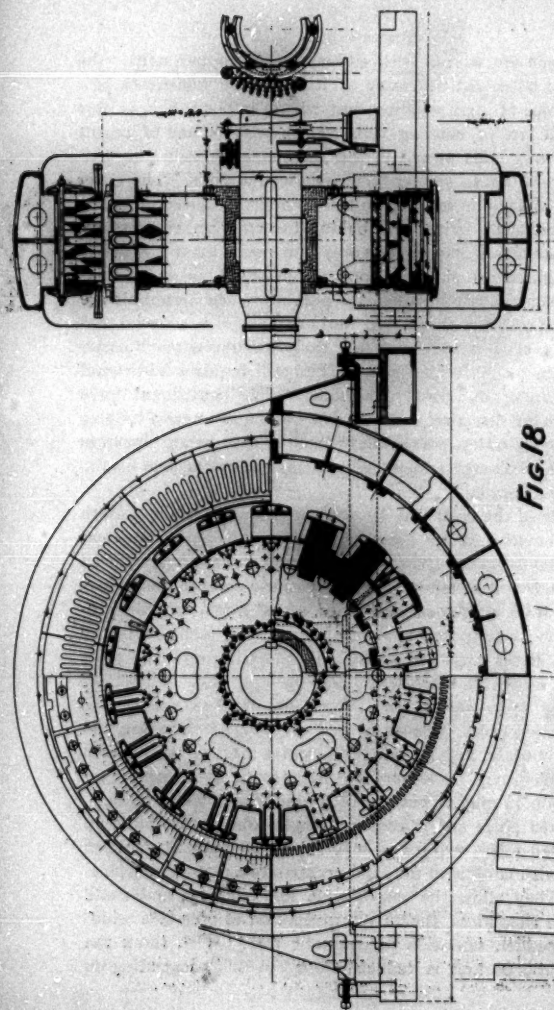
Field-coils are wound with either wire or copper strip; the number of poles and necessary exciter pressure sometimes prohibit the use of strip winding, but wherever possible it is now used. The art of bending thin copper strip is one of recent development; coils wound in this manner have radiation constants several times greater than wire-wound coils. The outer surface of the coil is exposed to the air and thin sheets of paper separate adjacent strips; by baking the coils under pressure, the separate layers may be cemented into a solid mass. Wooden or fibre washers are placed at top and bottom of coil and insulation between the winding and the pole core; the terminals are riveted and soldered to the strip and are made of a material that does not crystallize by vibration. Strip-winding is much easier to retain in place at high speeds, but still requires additional retainers under abnormal conditions. The centrifugal force acts in a radial direction and with few poles may cause a bulging of the winding unless prevented by such devices as are shown in Fig. 19, which illustrates field-coil sections and methods of insulation in use at present.

The ends of the coils may be either round or straight. With high-speed machines, it is necessary to relieve the pole as much as possible from supporting the coil, and straps are commonly placed over the ends and fastened, independently of the pole, to the revolving rim. With slow-speed machines, a cast-metal retainer projecting over the exposed portion of the pole is fastened to the pole-end. Brass rings are occasionally placed around the poles to prevent injury from accidental field opening.

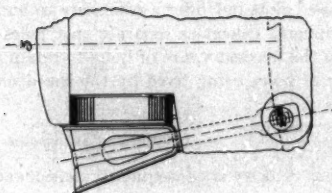
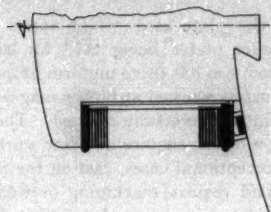
POLES, POLE-SHOES, AND METHODS OF FASTENING.

The various poles, pole-shoes, and methods of fastening the same are shown in Fig. 20, which illustrates most of the modern forms. Poles may be either of solid section, steel casting or wrought iron, or may be built up of laminations of rolled plate.

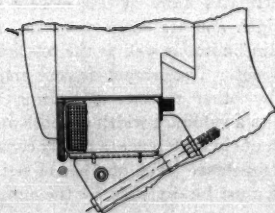
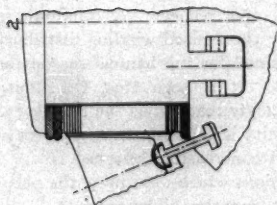
Laminated poles are of known strength and section built up into an even form, require no machine work, may be made in one piece with laminated rim, and necessitate a rectangular pole-section. They allow the use of wide slot openings and small mechanical clearances, the easy introduction of pole-face windings, the sudden variation of magnetic flux. With them the effective cross-section is reduced from 5 to 10%, depending on

**Fig. 18**

High-speed Water-wheel Construction.

*Fig. 19.*

Field-Coils.



the thickness of the plate used, which varies from 0.0125 to 0.125 in., the thicker plates being used for large mechanical stresses. Laminated iron has more uniform properties than cast metal and may be safely worked at higher magnetic densities.

Cast poles are almost universally of steel. They are likely to contain sand or blow-holes, require machine work for mounting unless, as in very exceptional cases, cast on the rim. The sides may be irregular and require machining or wedges for fitting field coils. Cast poles may be made of any desired section, suffer no reduction in effective cross-section and are easily held by bolts. If the tip or shoe is also solid, small gaps require closed or partially closed slots but offer a resistance to hunting. With very high peripheral velocities separate cast poles become impossible due to the necessary size of bolts to retain them.

The number of poles being fixed by the speed and frequency by the relation

$$\frac{\text{No. Poles} \times \text{rev. per. min.}}{120} = \text{frequency, in cycles per second.}$$

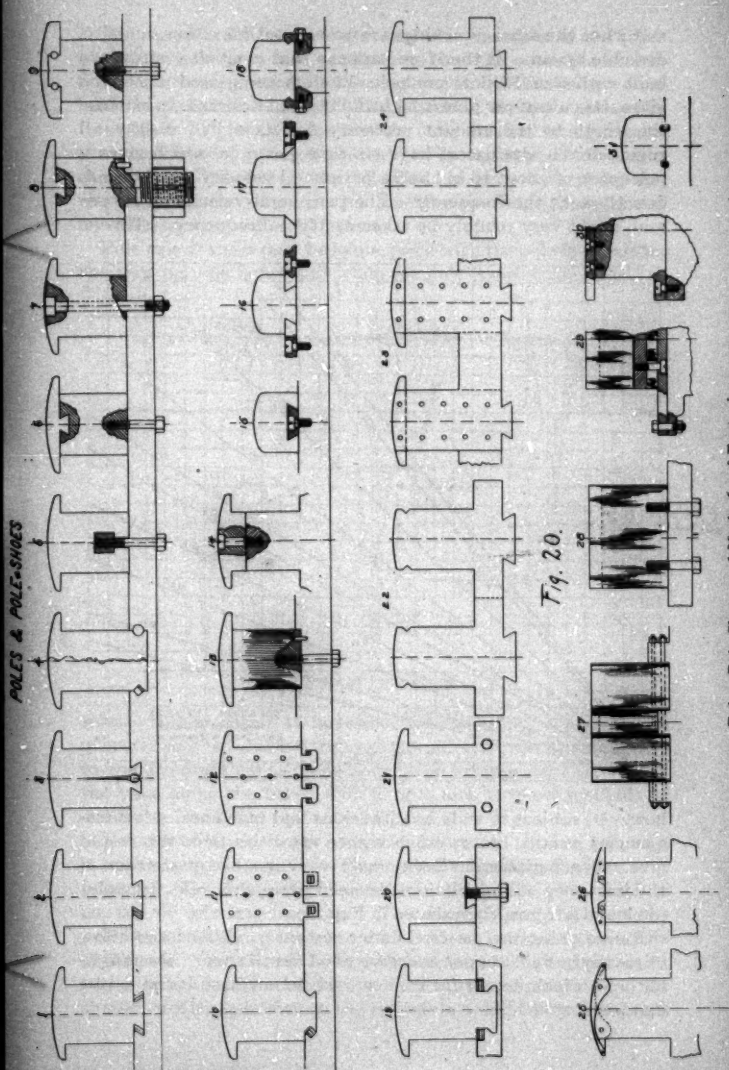
The peripheral velocity is consequently dependent on the pole pitch.

Peripheral velocity (ft. per min.) = $10 \times \text{pole-pitch (ins.)} \times \text{cycles per second.}$

The accompanying sheet, Fig. 21, shows clearly the relations and limitations in this respect. A minimum pole-arc being practically fixed by the desired winding distribution, the necessary gap is determined for mechanical reasons and economical magnetic densities. It is seen that the limiting peripheral velocity is more quickly reached as the frequency increases. If the peripheral velocity is kept constant, it is not always possible to save in material by increasing the speed.

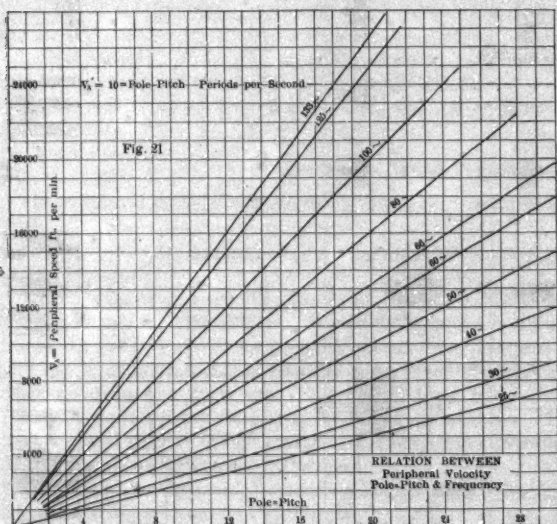
The natural relations which determine the peripheral velocity may be seen in part from the following:

The slot-depth is fixed by electrical reasons, and for a given line of machines approximates more or less closely to a constant value. The slot-width and its relation to the slot-depth are variables, only within limits, as well as the relation between the widths of tooth and slot. The current-density and space-factors being determined by other reasons of heating and dielectric strength, there results a value for width of tooth and slot and for the amperes per inch of circumference, a nearly constant quantity for a given type of machine. The number of slots per pole for two- or three-phase must be divisible by the number of phases.



Poles, Pole-Shoes and Methods of Fastening.

and when the same punchings are to be used for either, must be divisible by six. It therefore happens that most alternators are built with 6 or 12 slots per pole, 12 slots being used where the kilowatts output per pole is high and it is not desirable to increase the length to the amount necessary for six slots. Nearly all engine-driven alternators have six slots per pole, which gives a pole pitch of about 10 in., and a peripheral velocity which varies directly with the frequency. The peripheral velocity in ft. per min. might very roughly be taken as $100 \times \text{frequency}$. This is



however, subject to wide modifications and machines of low frequencies usually run at much higher velocities than this would give. The peripheral velocity may vary as the square root of the frequency. The relations between peripheral velocity, pole-pitch and frequency are shown in Fig. 21.

Round poles may be used under certain conditions and allow of saving in field copper and give good ventilation. Rectangular poles which depart far from square do not best utilize active material.

The desired relation between magnetic densities in the pole-core and at the pole-face necessitates that the pole-shoe extend beyond the core around the circumference. This also serves to hold the field-coil in place. The length of the pole-arc varies from 50 to 70% of the pole-pitch; the relation being a compromise between opposing tendencies. In one type of alternator the tip is not extended; the coil is held in place by a wedge extending between poles; in this machine the magnetic relations are necessarily of different values.

Pole-tips or shoes may be in one piece with the pole or separate; the shoe may be laminated while the pole is either laminated or

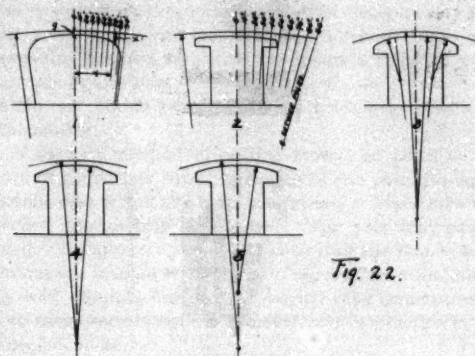


Fig. 22.

Forms of Pole Shoes.

solid. It is necessary to have the field-coil easily removable and in some cases to be able to remove the poles in order to gain access to the armature coils where there is no arrangement for sliding the yoke along the base. No. 6, 8, 9, and 14 show methods of attaching laminated tips to solid poles.

Pole 1 is of representative form for laminated section, although it might be used for solid. The method of holding the pole is of interest. The dovetail is cut diagonally in the rim which is usually of solid steel section. The dovetail projection on the pole is straight, *i.e.*, parallel to shaft. There is a key on each side of the pole. One side of the key—that against the pole—is straight, while the other side is inclined to fit the groove in the rim. The shoulders of the pole rest on the rim while a slight clearance exists

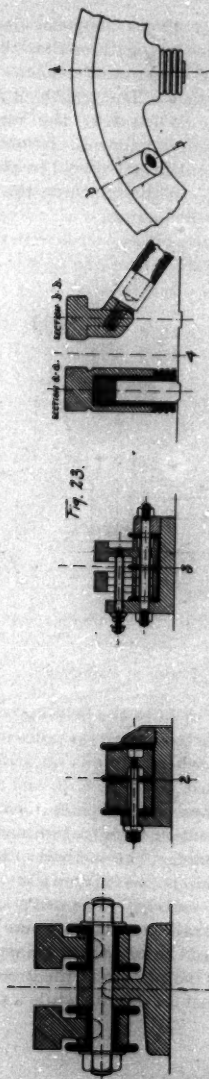


Fig. 23.

Collector-Rings.

at bottom. The heating of the pole will tighten the joint, the keys allow the pole to be accurately centered and by the insertion of shims under the shoulders, the clearance may be changed slightly. Poles are interchangeable and with end-plates against keys cannot become loose during operation. The laminations are held in place by bolts or rivets and are assembled as solid pieces. The dovetails are cut in the rim by first cutting out the rectangle with a slotter and then the angles with an end-milling cutter.

Pole No. 2 is a modification of No. 1. The dovetail is cut straight and the two taper keys are on the same side of the pole.

Pole No. 3 is the same general plan. Instead of using keys the pole is slotted at the bottom and after being placed in the dovetail, a round key with inclined parts is driven in the central hole spreading the iron sufficiently to insure a tight fit. There may be two or more slots.

Pole No. 4. Shows two methods of holding pole which are self-explanatory.

Fig. 5 shows a method of bolting laminated poles to yoke. A square or round bar runs lengthwise of the pole through the laminations into which the bolts are tapped. The contact-area and section are slightly diminished. The pole may easily be saturated. An alternative method is to sink the bolt-head into the laminations instead of the bar. This method of holding the pole is well adapted for use on engine-type generators. It allows of easy assembling and removal, and in practice is found not to become loose.

Fig. 6 is a solid pole with laminated tip dovetailed and the whole bolted to the yoke.

Fig. 7 is a solid pole bolted through from top.

Fig. 8 is a curious and apparently expensive foreign construction. In this case the pole is round and is fixed in position, by a dowel-pin.

Fig. 9 is of interest as showing a unique method of holding pole-tips.

Fig. 10 shows a method of retaining poles used by the Allgemeine Electricitäts Gesellschaft for machines with high peripheral velocities.

Fig. 11 shows a method for retaining poles where the rim consists of laminated iron as well as the poles, and where the extended pole-tip is in one piece with the pole-core. The laminations in the rim are built up in short sections of from one to two

inches, which are riveted and the whole held together by through bolts. The pole laminations are alternated as shown to match the similar sections of the core and the whole is held by taper keys as shown.

Fig. 12 shows a design for the same purpose as the preceding. The pole is built up solid from laminated iron and inserted end-wise into the rim. It is there drawn tight against the rim by taper keys. This is used on high-speed machines of large output and has proved a very satisfactory method where the mechanical stresses are great.

Fig. 13 shows a foreign method of countersinking a round pole into the rim, and the use of a dowel-pin to prevent turning. With a cast-iron rim this construction is good, but also expensive. The added security against tilting of the pole is not great.

Fig. 14 shows an unusual construction, sometimes used in small machines, of casting the pole in one piece with the rim. The shoe which may be solid or laminated, is screwed on from the top. Should the poles come unevenly spaced on the casting it is difficult to compensate therefore by a small shifting of the shoe.

Figs. 15, 16, 17, 18, and 31 illustrate different methods of holding the poles on inductor alternators.

Fig. 15 illustrates present practice in this country. Fig. 31 illustrates a cheap method of holding by babbitt which can only be used where the centrifugal force is small.

Fig. 19 is the same method as in Fig. 12, except that the keys force the pole up instead of drawing it down. It does not appear to have any compensating advantage.

Fig. 20 shows a method which is often cheaper than the dovetail construction.

Fig. 21 shows a foreign construction. The windings placed directly on the poles which are then mounted adjacent to each other and supported entirely by the through bolts as shown.

Fig. 22 illustrates a construction used in this country where the pole-tip is not extended and where the yoke-ring is laminated and made in one piece with the poles. The rim may be used for a fly-wheel or not as conditions prescribe. The field-coil is retained by a wedge between adjacent poles.

Fig. 23 is a very interesting construction used for high-speed machines. The lamination embraces two poles and extends on one side to the air-gap and on the other to the bottom of the pole-tip. The plate used is 0.125 in. thick and a number of similar plates are built up together. As the plates cover two poles but

one-half of the rim-section between is iron, and by building up three plates of each kind before reversing, we have numerous ventilating ducts alternating with the iron section extending across the core and affording excellent ventilation. Numerous bolts pass through the laminations, making the whole self-contained and independent of the dovetail supports which are used merely for construction and alignment. The pole-tips are separate and are inserted between the projecting laminations after the coils have been put in place. Rods are then run through, securely fastening the tips in place. In this manner the central part of the pole face is continuous, while the edges where the tips project, are broken.

Fig. 24 is similar to 22 except that the pole-tips project and the poles are wound by hand with flexible cable after the field-iron is assembled.

Fig. 25 is a construction used for small high-speed machines such as are suited to turbine work. The pole and central part are made in one piece and are riveted in sections the whole being held together by long bolts or rivets. The pole ends in a double, curved surface which is reversed every alternate section. Two adjacent sections of the pole-shoe are riveted together and are then inserted into the corresponding places in the pole-end. Long rods running through both hold the shoe in place.

Fig. 26 is a variation of the same method.

Fig. 27 is a method of retaining the poles by double row of bolts, and Fig. 28 of simply tapping directly into the laminations.

Fig. 29 shows each pole with a separate base which latter is bolted to the rim and Fig. 30 another method of bolting and a detachable pole-shoe.

FORM OF POLE-SHOES.

The distribution of the magnetic flux on different parts of the pole-face, is largely determined by the length of gap at any point to which the magnetic density is almost inversely proportional. If we have one slot per pole per phase, the wave of electromotive force practically coincides with that of field distribution. With more than one slot per pole per phase, the tendency is for the wave of e.m.f. to approximate a sine form independent of the law of distribution of the magnetic flux. If with open slots the strength of the field be not graded near the pole-edge, harmonics are introduced into the wave form. There are several methods of shaping the pole-face in order to get the desired sine wave with a sufficient degree of approximation. (Shown in Fig. 22.)

No. 1 shows the pole on an S.K.C. inductor alternator. Here the gap is so laid out as to give a theoretically perfect sine wave. The distance between the centers of two consecutive poles in this type of machine represents 360° electrical. Starting from the centre of the pole with a gap equal to g , we have for the gap g^1 , at any point r at an angular distance from the centre line equal to α electrical degrees.
$$g^1 = \frac{g}{\cos \alpha}$$

Fig. 2 is for a machine the adjacent poles of which are of opposite polarity. Here the distance between pole centres represents 180° electrical and the pole-face is laid off as before with this difference.

Figs. 3, 4, and 5 show methods of approximation which may give results which agree quite closely with those obtained from a theoretical curve. Fig. 3 is a compound curve. Fig. 4 has the central part of the pole-arc drawn from the centre of the armature. The edges of the poles have straight bevels. In Fig. 5 the pole-arc is drawn with a radius less than that from the armature centre to gap. With proper judgment any of these methods will be found to give satisfactory results.

COLLECTOR RINGS.

A great disadvantage in the revolving-armature type of alternator is the difficulty of taking high-pressure current from the machine. The continuity of insulation must be broken and the exposed brushes and collector are always possible sources of danger. While, with the inductor alternator, we have no moving wire and consequently no moving contacts; with the revolving-field generator the low pressure exciting current must be led into the field-coils by means of collector rings. The forms in common use are shown in Fig. 23. The rings are usually made of cast iron, and carbon brushes are employed. Several brushes per ring are used to allow for repairs or adjustment without interruption of service. The collector is preferably made open especially if much heat is generated. Different methods of supporting and insulating the rings are shown.

A CONTRIBUTION TO THE THEORY OF THE REGULATION OF ALTERNATORS.

BY H. M. HOBART AND F. PUNGA.

The interesting paper recently contributed by Behrend to the proceedings of the INSTITUTE, has incited the writers to the preparation of the present paper, which sets forth their own views regarding the regulation of alternating-current generators.

It is unnecessary to refer to the theories of others, since these have so recently been discussed by Behrend*, who has shown by means of practical examples that none of these theories give correct results for different types of machines.

The theory which the writers describe in this paper has been tested on but a limited number of machines, but has in these cases given such excellent results as amply to justify its publication, in the hope that this will lead to its being subjected to further tests in impartial quarters. Moreover, the writers entertain the hope that the theory itself will, independently of practical examples, prove convincing in virtue of its inherent simplicity and clearness, and its freedom from hypothetical assumptions. Nevertheless its reliability must of course be demonstrated by testing it by a large number of practical examples of various types of machines. It is our intention to bring together such practical examples in a treatise on the design of alternating-current generators, in which this theory will be employed in the sections relating to voltage regulation.

The change in the voltage of a constantly excited alternating-current generator when its load is varied in nature or amount, is

*TRANS. Am. Inst. Elec. Eng'rs., Vol. XX., p. 739.

chiefly occasioned by the magnetic flux set up by the current in the armature winding and linked with the turns constituting the winding. These lines may be classified according as they flow in one or the other of three paths, as shown in Fig. 1.

First Path—The lines never emerge from the armature. They consist of those which cross the armature slot from side to side, and those which are linked with the end connections.

Second Path—The lines emerge from the armature and cross the air-gap toward one end of the pole-shoe, and after passing along the pole-shoe, return across the air-gap to the armature from the other end of the pole-shoe.

Third Path—The lines, after emerging from the armature,

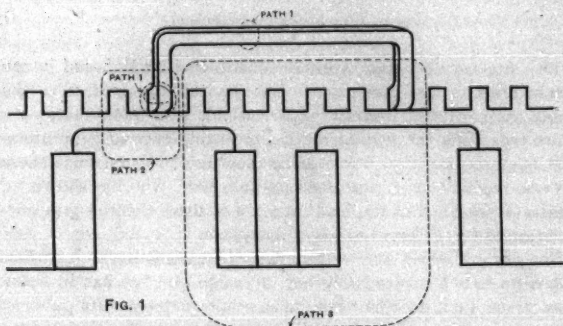


FIG. 1

traverse successively the air-gap, pole-shoe, magnet-core, yoke, adjacent magnet-core, and pole-shoe, and after again traversing the air-gap, re-enter the armature.

The lines following the *first path* are purely self-inductive, and all methods of treatment in which they are correctly handled are applicable also to our theory.

Hence for sine curves of electromotive force and current, one applies the recognized vector diagram of Fig. 2 in which

OA = The electromotive force generated in the armature winding by the lines crossing the air-gap = internal e.m.f.

OC = Current flowing in the windings.

$OD = BE$ = The reactance-voltage generated in the armature winding by the current OC flowing in it.

AB = Voltage-drop due to ohmic resistance.

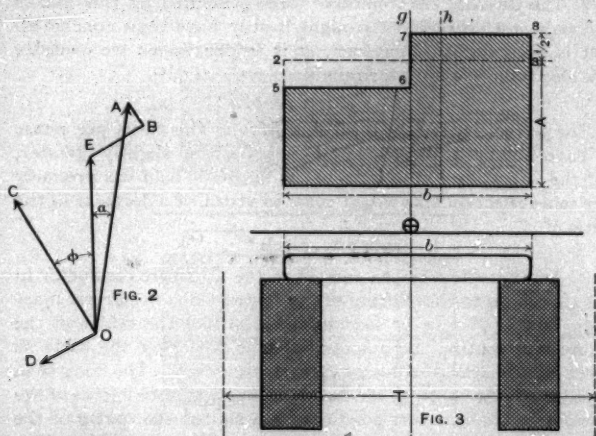
OE = Terminal voltage.

α = Angle AOE between internal e.m.f., OA , and terminal e.m.f. OE .

ϕ = Angle EOC between terminal e.m.f. OE and current OC .

The magnetic flux belonging to the second and third paths, can be best considered if we, for the moment, neglect the magnetic reluctance of the iron (armature laminations, magnet core, and yoke).

In Fig. 3 is shown a magnet-pole with a single armature conductor at the centre of the polar pitch. When the conductor carries no current, the magnetic flux across the air-gap will



be generated solely by the field magnet ampere-turns, and will be uniformly distributed over the pole-arc. It may be represented by the rectangular area 1 2 3 4, the spreading at the pole-tips being neglected.

Let us now consider the case when a current of i amperes flows through the conductor; the ampere-turns per field-spool will be denoted by A ; the total armature strength per pole, denoted by $i/2$, is, according to the conditions of load, to be added or subtracted from the field ampere-turns A .

In the case shown in Fig. 3, the left half of the pole-arc is subject to the influence of $(A - i/2)$ ampere-turns, the right half, to $(A + i/2)$ ampere-turns. The density of the magnetic flux is pro-

portional to these ampere-turns, since the magnetic reluctance of the iron is, for the time, neglected. The distribution of the magnetic flux may now be diagrammatically represented by the area 1 5 6 7 8 4 shown in Fig. 3. What now, is the effect of this distribution?

In the case under consideration where the conductor lies at the middle of the pole-pitch, the total number of lines of force entering the armature is unaffected by the armature current; *i.e.*, the area 1 5 6 7 8 4 is equal to the area 1 2 3 4 and what has been lost on the one side of the conductor has been exactly made up by the gain on the other side.

2. The internal electromotive force generated by this flux is not only not decreased, as might hastily have been concluded, but is even slightly increased, as is evident when we consider the electromotive force formula

$$E = k T N M \times 10^{-8}$$

The periodicity N , the total flux M , and the turns per phase T have not been altered, but k has become slightly greater, for the alteration in the form of the magnetic field has precisely the same effect on k as would occur in virtue of a decrease in the ratio of

pole-arc : pitch.*

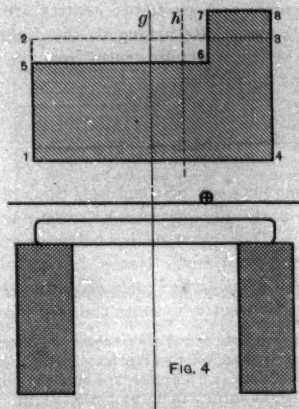
3. Another effect of the current in the armature conductor in Fig. 3, relates to the shifting of the central line of the total magnetic flux.† It may be seen from Fig. 3 that the centre of the figure representing the magnetic flux is no longer the same as when the armature-conductor carried no current. The line g then represented the centre of the flux; the magnetomotive force of the current in the armature-conductor has shifted the centre of the resultant flux distribution to the line h . These considerations are capable of being readily extended to the case of the flux distribution where the conductor occupies any other than the middle position opposite the pole-arc. The flux distribution in such a case is illustrated diagrammatically in Fig. 4, and the principal difference between this flux distribution and that of the previous case where the conductor occupied the middle position is seen to consist in a decrease in the

*The dependence of k upon the ratio of pole-arc to pitch was probably first pointed out by Kapp. It is very exhaustively treated on pages 82 to 85 of "Electric Generators."

†First pointed out by Blondel (*L'Industrie Electrique*, 1899.)

total number of magnetic lines due to the current in the conductor, whereas in the former case the total number of magnetic lines remained unchanged.

Of the three considerations enumerated above, we shall confine our attention to the first and third; since the influence of the change in k is comparatively slight, and since also it is, in actual practice, largely or altogether offset by the increasing magnetic reluctance of the teeth, consequent upon the increased local saturation brought about by distortion. Hence it is not only simpler, but actually more correct to disregard both of these opposing influences.



In order to study more carefully the influence of the armature magnetomotive force upon the magnitude and distribution of the magnetic flux, the diagram of flux distribution in Fig. 4 has been reproduced in Fig. 5. Since our purpose is to compare the flux distribution in the same machine under two different conditions we do not need to employ absolute values, but may represent by A the ordinate of the plane rectangular figure representing the flux distribution when there is no current in the armature-conductor, setting its abscissa, the pole-breadth, equal to b . The abscissa representing the position of the conductor measured from the right-hand end of the pole-face, may be designated by x . From the figure we obtain at once:

Number of magnetic lines entering armature when there is no current in the conductor = $A b$

Number of magnetic lines entering armature when the conductor carries the current $i = (A b - i/2) b + x i$.

The calculation of the amount of shifting of the centre of the total magnetic flux consists in ascertaining the position of the ordinate passing through the centre of gravity of the surface. When no current flows it is obvious that the magnetic and geometric centres are identical. But this identity must also occur in the extreme case represented in Fig. 6, where the armature magnetomotive force, $i/2$, equals that of the field-magnet spool. The magnetic and geometric centres are also identical in all intermediate cases. Returning to the diagram of Fig. 5, let the distance of the magnetic centre from the mid-pole position be designated by y ; then:

$$y = \frac{1}{2} \frac{x(b-x)i}{A b - (b i/2) + x i} *$$

Conductors lying between adjacent pole-tips are without influence upon the factors $x(b-x)i$ and $x i$, which are proportional to the distortion. They exert a direct demagnetising influence and thus affect the total flux. Hence, in obtaining the values of the factors $x(b-x)i$ and $x i$, only those conductors are to be considered which lie directly opposite the pole face. But in ob-

*This formula is derived as follows (Fig. 5):

Total surface $\times y = \text{surface } (1\ 2\ 3\ 4) \times (b/2) + \text{surface } (3\ 6\ 7\ 4) \times (b/2) + \text{surface } (5\ 8\ 9\ 6) \times (b/2 - x/2)$

Since surface $(1\ 2\ 3\ 4) = \text{surface } (3\ 6\ 7\ 4)$, we have

$$y = \frac{\text{Surface } (5\ 8\ 9\ 6)}{\text{Total surface}} \left(\frac{b}{2} - \frac{x}{2} \right)$$

The ratio $\frac{\text{Surface } (5\ 8\ 9\ 6)}{\text{Total surface}}$ is, however,

equal to

$$\frac{x i}{A b - (b i/2) + x i}$$

hence, in general

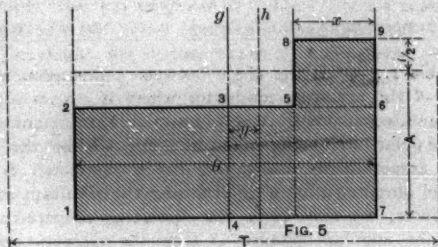
$$y = \frac{1}{2} \frac{x(b-x)i}{A b - (b i/2) + x i}$$

taining the value of $(b i/2)$, the total number of conductors per pole should be considered.

The calculation of the pressure-drop in a machine would by this method be far too laborious. But fortunately the method may be greatly simplified for the case of sine curves of electromotive force and current.*

SINE-WAVE ALTERNATORS.

In the many cases where we may for practical purposes assume a sine-wave form of electromotive force and current, the decrease in total magnetic flux as the result of the armature interference, may be attributed to and derived from the demagnetizing



ampere-turns, and the shifting of the flux centre, to the distorting ampere-turns.

The magnitudes of these values, as dependent upon the ratio pole arc: pitch are given in Table I.† for a single-phase alternator

*Since it is sometimes required to calculate the pressure-drop for machines where sine-wave assumptions are not permissible, this general analytical method is followed out to its conclusion in Appendix I., and therein are also set forth the uninteresting but essential steps leading up to the derivation of Table I. which result alone amongst the matter contained in Appendix I. is essential to the application of the theory to those alternators in which a sine-wave assumption is justifiable. For practical purposes this is generally found to be the case, hence the contents of Appendix I. possess interest only for those who wish to follow through the steps leading up to the practical results. Those who only wish to satisfy themselves of the soundness of the method, can do so by applying it to machines with which they are familiar, in the way illustrated in this paper.

†The derivation of Table I. is given in Appendix I., as indicated in the preceding foot-note.

with one slot per pole, when loaded to an armature strength of $n i$ effective armature ampere-turns per pole.

TABLE I.
DEMAGNETIZING AND DISTORTING AMPERE-TURNS FOR THE CASE OF A
UNI-SLOT, SINGLE-PHASE ALTERNATOR.

	$b/\tau = 0.5$	$b/\tau = 0.6$	$b/\tau = 0.7$
Demagnetizing ampere-turns.....	$0.82(n i) \sin \phi'$	$0.78(n i) \sin \phi'$	$0.75(n i) \sin \phi'$
Distorting ampere-turns...	$0.11(n i) \cos \phi'$	$0.15(n i) \cos \phi'$	$0.20(n i) \cos \phi'$

In Table I.: ϕ' is the angle between pole-centre and that position of the armature-conductor where it carries maximum current and, consequently, exerts its maximum magnetomotive force, the polar-pitch being taken as 180° . While the demagnetizing ampere-turns are to be directly deducted from the field-spool ampere-turns in determining the resultant magnetomotive force, we may from the distorting ampere-turns, determine the angular distance, β , from the magnetic centre by means of the equation degrees shift of the magnetic centre β

$$= \frac{\text{Distorting ampere-turns per pole}}{\text{Air-gap ampere-turns per pole}} \times 90^\circ*$$

The influence of the pole-arc on the demagnetizing and distorting ampere-turns is of considerable interest. With increasing ratios of

Pole-arc : pitch

the demagnetizing ampere-turns very slowly decrease. But the distorting ampere-turns, on the other hand, increase, and very rapidly; in fact their rate of increase is as the square of the increase in the ratio of pole-arc to pitch. This circumstance may be of importance in the choice of the pole-arc. When, for instance, a certain closeness of regulation for $\cos \phi = 1$, is required, it may be distinctly advantageous to design the machine with a relatively small pole-arc and thus decrease the distor-

*It might be more exact in some cases to make some allowance for the magnetomotive force required by the teeth.

tion. But when it is required to obtain a given degree of regulation for $\cos \phi = 0$, one will obtain the best results by means of a larger pole-arc.

SINGLE-PHASE DISTRIBUTED WINDINGS.

It is relatively simple to extend the calculations to other types of winding. Thus, when the single-phase alternator has many slots per pole, or a uniformly distributed winding, both the demagnetizing and distorting influence will be somewhat less; since for the different sections of the winding the maximum magnetomotive force occurs when these sections occupy different positions with respect to the pole-centre. When for example one side of a winding covers one-third of the pole-pitch, it will be necessary to multiply the values given in Table I. for the armature interference, by 0.95. This quantity is designated the "breadth-factor" and has, for various types of winding, the values set forth in Table II.

TABLE II.

Percentage of polar pitch covered by one side of the armature winding.	"Breadth Factor"
20%	0.99
40%	0.94
60%	0.86
80%	0.76
100%	0.64

APPLICATION TO POLYPHASE GENERATORS.

Nothing new is encountered in applying these principles to the case of polyphase generators. One must merely first calculate the armature interference for one phase and then multiply the values thus obtained, by the number of phases. The ampere-turns are thus combined algebraically and not geometrically.* The correctness of this proposition is at once recognized when it is considered that all the phases are identical; for we have the same number of turns, and the same current

*An experimental proof for this assertion may be found in the table page 16a, which shows the agreement between observed and calculated values for 7 single-phase generators and for 11 three-phase generators.

per turn, and the current reaches its maximum value for all phases when at the same distance from the mid-pole face position.

In order to make the final forms of the expressions for the demagnetizing and distorting ampere-turns as simple as possible, we shall denote the effective ampere-turns per armature pole by $n i$, and combine the results of Tables I. and II. in Table III.

TABLE III.

GENERAL CASE FOR DEMAGNETIZING AND DISTORTING AMPERE-TURNS.

	Armature Ampere-turns (effective) per pole.		
	$b/\tau = 0.5$	$b/\tau = 0.6$	$b/\tau = 0.7$
Demagnetizing ampere-turns.....	$0.82 B n i \sin \phi'$	$0.78 B n i \sin \phi'$	$0.75 B n i \sin \phi'$
Distorting ampere-turns.....	$0.11 B n i \cos \phi'$	$0.15 B n i \cos \phi'$	$0.20 B n i \cos \phi'$

The application of these methods to the results obtained experimentally on a typical alternator, will suffice to show the method of applying this theory of the regulation of alternators. The machine investigated was one of the three-phase generators installed at the Shepherd's Bush Power-House of the Central London Railway. The rated output is 850 kw. at unity power-factor. The machine has 32 poles, and a speed of 94 rev. per min., the periodicity being 25 cycles per second. The pressure between terminals is 5000 volts, corresponding to 2880 volts per phase, and for each of the Y-connected armature windings.

The leading dimensions are set forth in the following specification:

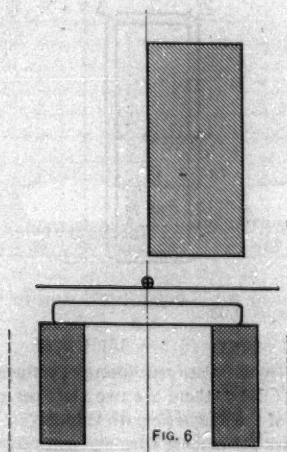
Armature diameter.....	3666	mm.
Gross width of armature core between flanges.....	368	"
Number of ventilating ducts.....	5	
Width of each ventilating duct.....	13	mm.
Effective width of armature core.....	274	"
Number of slots.....	192	"
Number of slots per pole per phase.....	2	
Depth of slot.....	92	mm.
Width of slot.....	33.4	mm.

FIELD.

Length of pole-arc.....	228	mm.
Polar pitch.....	360	mm.
Ratio of pole-arc to pitch.....	63.3%	
Radial length of magnet-cores.....	840	mm.
Diameter of bore of field.....	3644	mm.
Radial depth of air-gap.....	8	"
Dimensions of cross-section of magnet-core.....	16.5×37	sq. cm

WINDING.

Number of armature-conductors.....	2688	
Number per slot.....	14	
Number of turns per pole and per phase.....	14	
Effective armature ampere-turns per pole and per phase at full-load current of 98 amperes.....	1380	
Each armature-conductor consists of 26 strands of No. 17 B. W. gauge.		
Mean length of one armature-turn.....	161	cm.
Embedded length.....	55	"
Free length.....	106	"



We shall first calculate the short-circuit current, since this is generally experimentally observed, and constitutes a good test of the theory. The estimation of the short-circuit current requires a determination of the inductance of the winding. With

straight-sided slots a good approximation to the inductance of the embedded part may be obtained by elementary magnetomotive force calculation thus:

Let D = depth of slot in centimetres.

d = depth above top of winding in centimetres.

W = width of slot in centimetres.

Number of lines per ampere-turn per centimetre of embedded length, may, for the case of the inductance of the winding in a single slot, be taken as approximately equal to

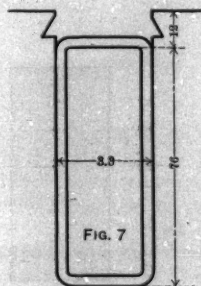
$$\frac{4\pi}{10} \frac{\frac{1}{2}(D-d)+d}{W} = 0.63 \frac{D+d}{W}$$

In the case in question (see Fig. 7)

$$D = 9.2$$

$$d = 1.2$$

$$W = 3.3$$



$$\text{Number of lines} = 0.63 \times \frac{9.2 + 1.2}{3.3}$$

= 1.99 per centimetre of embedded length and per ampere-turn. Now, there are two slots per pole per phase, hence the length of the magnetic path through air is doubled and the number of lines per ampere-turn per centimetre of embedded length becomes $1.99/2 = 1.00$.

It has been demonstrated* that the number of lines per ampere-turn per centimetre of free length may be taken at from 0.4 to

*" Modern Commutating Dynamo Machines, with Special Reference to the Commutating Limits," by H. M. Hobart, *Proc. Inst. Elec. Engrs.*, Vol. 31, p. 170.

0.8. As a rough approximation we may estimate them as follows:

0.8 lines for 1 slot per pole and per phase

0.7 " " 2 " " " " " "

0.6 " " 3 " " " " " "

Thus in the case under consideration we obtain: $55 \times 1.00 + 106 \times 0.7 = 55 + 74 = 129$ lines per ampere-turn†.

The inductance per spool of 28 turns is

$$28^2 \times 129 \times 10^{-9} = 0.00100 \text{ henrys}$$

and the reactance is

$$2\pi \times 25 \times 0.00100 = 0.157 \text{ ohms}$$

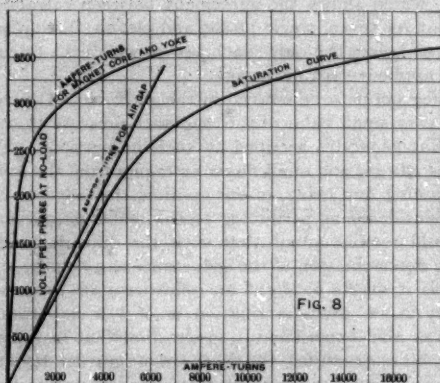


FIG. 8



FIG. 9

As there are 16 such 28-turn spools per phase, the reactance per phase is

$$16 \times 0.157 = 2.51 \text{ ohms.}$$

The reactance-pressure with full-load current of 98.5 amperes is

$$98.5 \times 2.51 = 248 \text{ volts}$$

From the saturation curve of Fig. 8, we find that 500 ampere-turns per field-spool are necessary for this voltage.

The demagnetizing ampere-turns equal (see Table III).

$$3 \times 0.77 \times 0.96 \times 1380 = 3050$$

Hence, one requires

$$3050 + 500 = 3550$$

†It is interesting to note that the end connections contribute more to the total inductance than the slots.

field ampere-turns per pole to generate full-load current in the short-circuited windings. The observed value was 3625 ampere-turns.

This agreement, within two per cent is, of course, better than can be relied upon, or indeed than is at all necessary; but by this method it appears that an accuracy of from five to ten per cent is generally attainable, in predetermining the excitation corresponding to a given short-circuit current.

We have checked the experimentally observed short-circuit current on 18 different machines and in 89% of all cases the agreement was within seven per cent. These are given in Table IV., which shows the agreement between calculation and experiment for seven single-phase and eleven three-phase machines, these being the only machines to which the calculation has been applied:—see next page.

An interesting point to be noticed in the short-circuit current relates to the very small value of the reactance-pressure as compared with that generally ascribed to such proportions. This arises from the elimination of all fluxes emerging from the armature, the remaining flux being, in our opinion, the only one correctly to be considered as pertaining to the reactance-pressure. Now, we should readily admit that with the data at present accessible, the determination of the inductance can only be very rough. But as it exerts so slight an influence upon the result, this inaccuracy in its predetermination is of less importance. In fact, it was the experimental observation that in a great number of machines examined, the short-circuit current deviated but slightly from that corresponding to a magnetomotive force equal to that of the field-spools, that led one of us in a series of articles in which he collaborated,* to neglect the inductance-flux as directly affecting the value of the resultant flux, and to employ it merely in deriving the angular distance between mid-pole position of the centre of one side of the armature coil, and the position corresponding to maximum value of the current in the armature coil. This theory gave very satisfactory results, checking observed values more closely than any other method available. But of course the present method which is supported by a sound theory, is distinctly preferable and gives, in fact, still higher accuracy.

In the predetermination of the characteristic curves, one has frequent occasion to employ the following values:

*" Design of Alternators," *Engineering*, Vol. 70, p. 107.

TABLE IV.

Type of Machine.	Rated output in kw.	No. of Poles.	Periodicity (Cycles per Second.)	Ampere Turns on the Field Spool.		Percentage Deviation between Calculated and Observed Results.
				Observed.	Calculated out of Short-circuited current.	
Single-phase Generator...	75	8	60	4000	4560	14
"	120	14	125	2900	2840	2
"	100	20	60	2875	3030	5
"	60	10	125	2900	2800	3
"	300	32	125	3650	3510	4
"	180	20	125	3250	3070	5.5
"	150	20	125	2950	2890	2
Three-phase generator, Y-connected...	360	12	60	3550	3880	9.3
"	300	12	35	5255	5050	4
"	225	6	25	6750	6300	7
"	150	14	60	3400	3500	3
Three-phase generator, Y-connected...	150	12	60	4100	3940	4
"	75	20	25	4800	4900	2
"	250	24	25	7850	7930	1
"	100	12	60	3950	3900	1.5
"	150	12	60	3850	3850	0
"	250	16	60	3800	3800	0
"	200	48	40	5300	5550	5

Ohmic (iR) drop per ampere, 0.33 volts.

Reactance-pressure per ampere, 2.52 volts.

Demagnetizing ampere-turns per ampere = $3 \times 0.77 \times 0.96 \times 14 \times \sin \phi' = 31 \sin \phi'$ (see Table III.)

Distorting ampere-turns per ampere = $3 \times 0.17 \times 0.96 \times 14 \times \cos \phi' = 6.8 \cos \phi'$ (see Table III.)

Calculation of the armature interference for full load and $\cos \phi = 1$.

In the diagram of Fig. 9, the vectors have the following magnitudes:

$$OE = 2880 \text{ volts.}$$

$$EB = 98.5 \times 2.52 = 248 \text{ volts.}$$

$$BA = 98.5 \times 0.33 = 32.5 \text{ volts.}$$

$$OA = \sqrt{(OE + BA)^2 + (EB)^2} = 2915$$

Hence

$$\alpha = \sin^{-1} \frac{248}{2915}$$

$$= \sin^{-1} 0.08$$

$$= 4.8^\circ$$

The distorting ampere-turns equal $8.6 \times 98.5 \times \cos \phi' = 670 \cos \phi'$.

ϕ' is not yet determined, but it is evidently small—of the nature of 15° —and hence $\cos \phi'$ is approximately equal to unity and the armature distortion to 670 ampere-turns.

For 2915 volts per phase we see from the straight sloping line in Fig. 8. that the air-gap reluctance requires 5600 ampere-turns. Hence β which equals

$$\frac{\text{Distorting ampere-turns}}{\text{Ampere-turns for air-gap}} \times 90^\circ$$

is equal to

$$\frac{670}{5600} \times 90^\circ = 10.8^\circ$$

$$\phi' = \alpha + \beta = 4.8^\circ + 10.8^\circ = 15.6^\circ*$$

*If greater accuracy should be considered desirable, one could, now that a better approximation of ϕ' has been obtained, make a final precise calculation of β , as follows:

$$\begin{aligned}
 \beta &= \frac{\cos 15.6^\circ}{\cos 0^\circ} \times 10.8^\circ \\
 &= .963 \times 10.8^\circ \\
 &= 10.40 \\
 \text{and } \phi' &= 4.8^\circ + 10.4^\circ = 15.2^\circ
 \end{aligned}$$

The demagnetizing ampere-turns

$$\begin{aligned}
 &= 31 \times 98.5 \times \sin \phi' \\
 &= 31 \times 98.5 \times .262 \\
 &= 800
 \end{aligned}$$

From the saturation curve in Fig. 8 we find that 7900 ampere-turns are required for 2915 volts per phase. Hence the total field excitation required for full-load current of 98.5 amperes at unity power-factor, is

$$800 + 7900 = 8700$$

But at this increased magnetomotive force the leakage coefficient of the magnetic circuit has also increased, and at the high saturation values often met with in modern alternators this may amount to a very appreciable influence, and we take account of it in our theory; though in the interests of simplicity, only in a roughly approximate manner, as anything approaching an exact estimation requires too much time* to be employed in practical designing work.

We follow Hopkinson's definition for the leakage coefficient, namely

$$\text{Leakage coefficient} = \frac{\text{Useful flux} + \text{leakage flux}}{\text{Useful flux}};$$

the leakage flux is equal to a constant $\times$ the ampere-turns per field-spool multiplied by

$$\frac{h(b+15)}{a} \text{ (see Fig. 10)}$$

for cores of rectangular cross-section and by

$$\frac{h+b}{a}$$

for cores of circular sections.

The constant may be taken at about 1.7%. It is

*See Kapp's "Elektromechanische Konstruktionen," 1902, p. 28; Arnold, E. T. Z., 1902, p. 251.

assumed that pole-arc is between 0.55 and 0.70 of pole-pitch.

For no-load and 2915 volts per phase we obtain a leakage coefficient equal to 1.20.*

At full load the leakage coefficient increases to

$$1 + 0.20 \times \frac{8700}{7900} = 1.22$$

In Fig. 8 are plotted in addition to the right-hand curve of total saturation, two other curves, the intermediate one corresponding to the ampere-turns required for air-gap and teeth, and the left-hand curve corresponding to the ampere-turns required for magnet-core and yoke. For our purpose it has been sufficient to take the saturation for air-gap as a straight line through the origin tangent to the curve of total saturation, and to derive the curve for magnet core and yoke from the difference of the other two curves, taking into account the ampere-turns for the teeth at high saturation.

For a no load potential of 2915 volts per phase (*OA* of Fig. 9), 1950 ampere-turns are, from the left-hand curve of Fig. 8, found to be required for magnet core and yoke. But so far as relates to the magnetomotive force required for magnet core and yoke, the increase in the leakage coefficient from 1.20 to 1.22 has the same effect as would result from an increase in voltage per phase from 2915 to

$$\frac{1.22}{1.20} \times 2915 = 2960 \text{ volts}$$

with constant leakage coefficient. From the left-hand saturation curve of Fig. 8 it is found that for 2960 volts, the magnet core and yoke would require 2050 ampere-turns.

$$2050 - 1950 = 100 \text{ ampere-turns}$$

is the increased excitation required for magnet core and yoke in virtue of the increased leakage coefficient.

From this we finally find that a total magnetomotive force of

$$8700 + 100 = 8800 \text{ ampere-turns}$$

*Ampere-turns per field-spool = 7650.

$$h = 25 \quad b = 37 \quad a = 15$$

$$\text{Total useful flux} = M = \frac{2915}{4.44 \times 448 \times 25 \times 10^{-8}} = 5.8 \times 10^8$$

$$\text{Leakage coefficient} = 1 + \frac{1.7 \times 7650 \times 25 (37 + 15)}{5.8 \times 10^8 \times 15} = 1.20$$

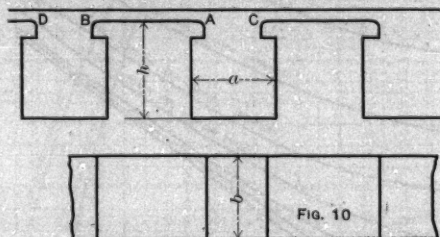
per field spool is required to obtain 5000 terminal volts (2880 volts per phase) for the full-load current of 98.5 amperes at unity power-factor.

To obtain the inherent regulation,* one compares the voltage per phase (2880) thus obtained, with the pressure corresponding to the same excitation at no load.

This is found from Fig. 8 to be 3030 volts, and the inherent regulation is therefore:

$$\frac{3030 - 2880}{3040} \times 100 = 4.9\%$$

In this manner the field ampere-turns have been estimated for various pressures and various amperes output and the results are plotted in Fig. 11. Experimental confirmation of the upper



curve (that for 2880 volts per phase) is found in the group of observed points plotted in Fig. 11 for these conditions of load and pressure. In Fig. 12 the right-hand saturation curve for full-load current of 98.5 amperes at unity power-factor, has been derived by observation, while the plotted points are taken from the calculated curves of Fig. 11. The left-hand curve of Fig. 12 is merely the no-load saturation curve which has been reproduced from Fig. 8.

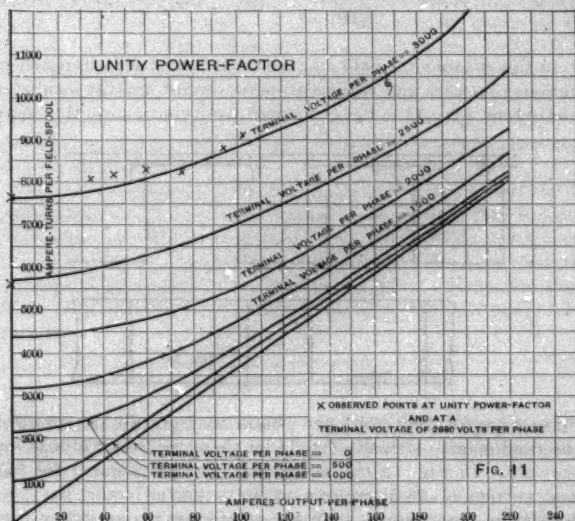
*We define the "inherent regulation" for a given power-factor, as the percentage increase in pressure occurring when the load is decreased from rated full-load current to no load, the excitation remaining constant.

The "excitation regulation" is also a useful conception, and for a given power-factor is defined as the percentage increase in the excitation required to maintain constant terminal pressure, as the load is increased from no load to rated full-load amperes.

CALCULATIONS FOR $\cos \phi = 0$,

For a power-factor of zero, the calculations become exceedingly simple. The armature distortion becomes equal to zero, but the demagnetizing ampere-turns have a great influence upon the results. The ohmic drop can be altogether neglected because of its vector position, while the reactance pressure swings nearly into phase with the terminal pressure.

For full-load current of 98.5 amperes, the calculation is as follows (see Fig. 13):



$$EB = 248$$

$$AO = OB \text{ (approximately)} = OE + EB \\ = 2880 + 248 = 3128.$$

Demagnetizing ampere-turns = 3050

Ampere-turns per field-spool required to generate 3128 volts = 9400.

$$\text{Total} = 3050 + 9400 = 12450$$

$$\text{Leakage coefficient} = 1 + 0.20 \times \frac{12450}{9400} = 1.27$$

Increase in excitation required in virtue of increased leakage coefficient = $4100^* - 3000 = 1100$ ampere-turns.

Total excitation per field-spool required for 5000 terminal volts (2880 volts per phase), for 98.5 amperes output at $\cos \phi = 0$ is, therefore,

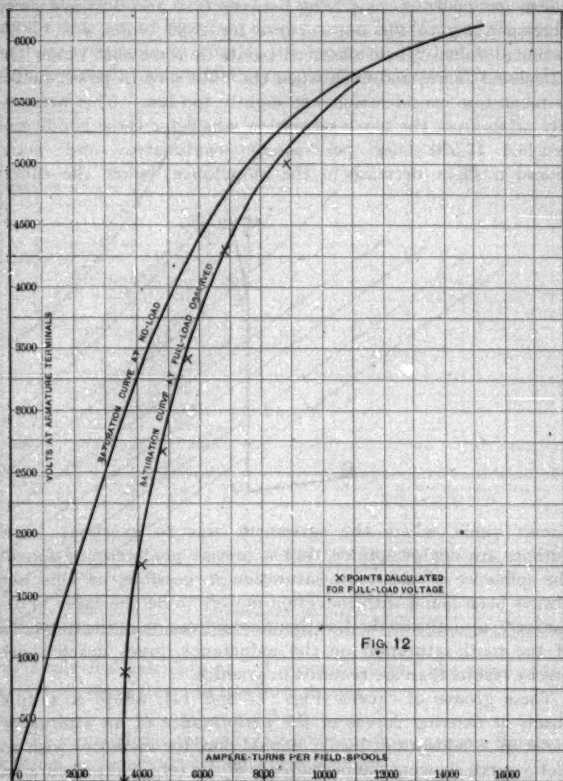
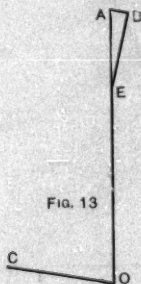


FIG. 12

*4100 and 3000 are the excitations for magnetic core and yoke corresponding respectively to $\frac{1.27}{1.20} \times 3128 = 3300$ and to 3128 volts.

$$12\,450 + 1\,100 = 13\,550 \text{ ampere-turns.}$$

Corresponding to the group of curves of Fig. 11 relating to $\cos \phi = 1$, there has been prepared for $\cos \phi = 0$, the group of curves shown in Fig. 14. Experimentally observed points could, of course, not be obtained for $\cos \phi = 0$, but a number taken for values of $\cos \phi$ lying between 0.10 and 0.25 are given corresponding to the upper curve for 2880 volts, *i.e.*, 5000 terminal volts. These observed points lie somewhat below the calculated curve, and even when the difference in power-factor is taken into consideration, are slightly too low. This presumably arises from the tooth-saturation which for these conditions reached 17 500 lines per square centimetre, and occasioned a slight decrease in the inductance, below the short-

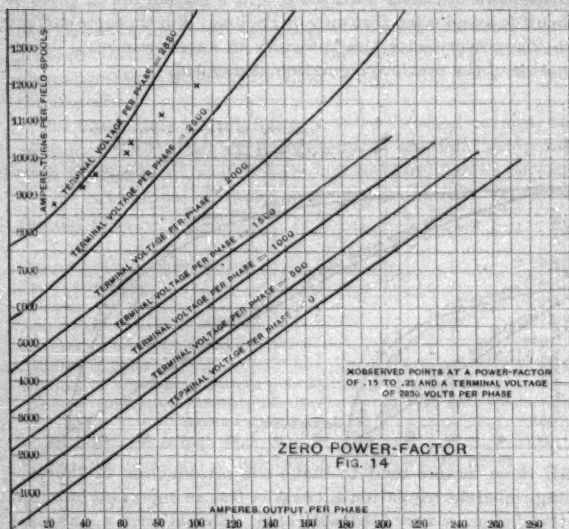


circuit value, where the agreement was so excellent. The authors are not of opinion that a precise predetermination of the influence of the tooth-saturation is possible, as this has always been found with induction motors to be the case. Fortunately, also, the method, without consideration of the influence of the tooth-saturation on the inductance, gives much more precise results than are required in practice.

These groups of curves (Figs. 11 and 14), afford a simple means of deriving curves of the performance of an alternator under all conditions of load. Should one, for instance, wish to plot a curve showing the dependence of the terminal pressure on the current for constant field excitation, one draws a horizontal line corresponding to this constant value of the excitation, and the intersection of this line with the curves for different pressures, give at once sufficient points for plotting the desired curve. This

has been done in Fig. 15 for four different cases, for which experimental data were also available. This agreement is very close.

For values of the power-factor intermediate between zero and unity, one carries out the calculation in the same manner as has been illustrated for $\cos \phi = 1$. One employs for the purpose the vector diagram of Fig. 2, in order to calculate OA and the angle α it is preferable to employ the graphical method, taking the values directly from the diagram, and thus avoid the necessity



for analytical calculations. β is obtained from the value of the armature distortion and one thus obtains

$$\phi' = \alpha + \beta + \phi$$

The remainder of the calculation proceeds in precisely the same manner as for $\cos \phi = 1$ and $\cos \phi = 0$.

The authors are of the opinion that in the course of time, it will become customary to specify merely the regulation for a pure inductance load; for, just as in the calculations this was shown to be the simplest case to handle, so also is it in practice, the case

which can be most cheaply, simply and accurately experimentally determined.

For approximately unity power-factor, it is exceedingly difficult, even with the best of wattmeters and other measuring instruments, to demonstrate the presence or absence of a slight difference of phase, and to measure it, although such a slight phase difference has a great influence on the regulation. For very low power-factors, *i.e.*, for $\cos \phi = 0$ as the limit, a phase difference of from 20° to 30° only slightly influences the result. Furthermore, for tests with $\cos \phi = 1$, a certain fall in speed is difficult to avoid when throwing on the load. For the same current at a low power-factor this difficulty in an experimental determination of the pressure regulation, is avoided.

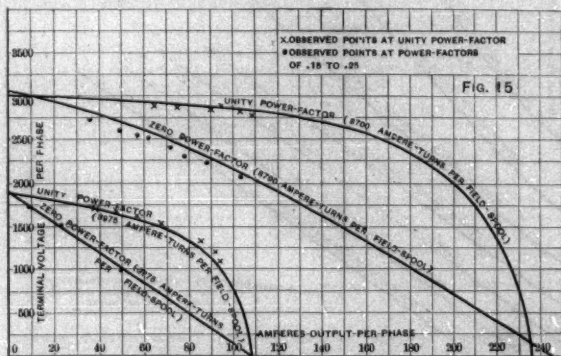


FIG. 15

All these factors tend to make the introduction of the percentage inherent regulation at $\cos \phi = 0$ as an important criterion of the design, a very desirable step. Should such a course be adopted generally, it would perhaps be necessary specially to consider those factors that may make the inherent regulation, at unity power-factor, poor, without impairing the inherent regulation at zero power-factor. These factors are:

1. The ohmic drop.
2. The ratio of pole-arc to pole-pitch. The influence of the ohmic drop amounts in the design we have considered to about 25% of the inherent regulation at $\cos \phi = 1$, and is negligible at $\cos \phi = 0$. Therefore it is necessary to specify the ohmic drop separately, and a resistance measurement with direct cur-

rent at the final temperature of the generator is quite sufficient for the purpose.

The ratio of pole-arc to pitch may have a decided effect, if quite abnormal dimensions are adopted; but inasmuch as other considerations, especially increased magnetic leakage, would prevent the use of a high ratio, the writers propose, for simplicity's sake, to disregard this factor. The writers put forward, therefore, the following specification as regards inherent regulation:

The generator shall, when loaded with the full rated current, lagging in phase behind the pressure by an angle corresponding to a power-factor of less than 0.2, at the temperature which the generator attains after 10 hours' full-load working, increase its normal pressure by no more than — per cent, when the load is thrown off.

The ohmic drop, calculated with rated full-load current, and a resistance determined experimentally at the final temperature with direct current, shall not amount to more than — per cent.

The calculation of these data may be briefly repeated in tabular form:

Output at unity power-factor.....	850 kw.
Type of winding.....	Y
Pressure per phase.....	2880
Amperes per phase at full load.....	98.5
Number of armature-turns per phase.....	448
Number of poles.....	32
Number of armature-turns per pole and per phase.....	14
Number of effective armature ampere-turns per pole and per phase.....	1380
Ratio of pole-arc to pole-pitch.....	0.63
Space taken by one side of the winding, per pole and per phase in per cent. of pole-pitch.....	33%
Breadth factor (B).....	0.95
Demagnetizing ampere-turns per ampere.....	31
Demagnetizing ampere-turns at full load (a).....	3500
Number of slots.....	192
Number of slots per pole and per phase.....	2
Depth of slot (D).....	9.2 mm.
Depth of slot above winding space (d).....	1.2 "
Width of slot at the root.....	3.3 "
Width of slot at the end.....	3.3 "
c.g.s. lines per ampere-turns per cm. length of winding in one slot.....	1.99
Additional lines in case of half open slots.....	
Total lines per cm. length of winding in one slot.....	1.99

c.g.s. lines per ampere-turns per cm. length of effective winding	1.00
c.g.s. lines per ampere-turns per cm. length of free winding	0.7
Length of one turn in iron (effective length)	55 cm.
Length of one turn in air (free length)	106 "
c.g.s. lines per ampere-turns due to effective length of a turn	55
c.g.s. lines per ampere-turns due to free length of a turn	74
c.g.s. lines per ampere-turns	129
Inductance of one coil	0.001 henrys
Reactance of one coil	0.157 ohms
Reactance of all coils per phase	2.51 "
Reactance pressure per ampere	2.51 volts
Reactance pressure per phase at full load	248 "
Total internal pressure	3128 "
Ampere-turns required for internal pressure (A)	9400
Demagnetizing ampere-turns (a)	3050
$A+a$	12450
Shape of magnet cross-section	rectangular
Width of magnet	37 cm.
Radial length of magnet core	25 "
Smallest distance between magnet cores midway along their length	15 "
Leakage c.g.s. lines corresponding to internal pressure	$= 1.24 \times 10^6$
Useful flux	6.2×10^6
Leakage coefficient	1.20
Leakage coefficient corresponding to internal pressure ampere-turns + demagnetizing ampere-turns	1.27
Ampere-turns for (field + yoke) corresponding to internal pressure	3000
Ampere-turns for (field + yoke) corresponding to the increased leakage factor	4100
Difference in ampere-turns (C)	1100
Ampere-turns per internal volt	9400
Demagnetizing ampere-turns	3050
Total ampere-turns at full load	13550
Internal pressure (E) corresponding to total calculated ampere-turns at no load	343 volts
Inherent regulation at zero power-factor	23%
Inherent regulation at power-factor up to 0.20 (estimated)	21%
Length of one turn	1.61 cm.
Total length of the turns of one phase	720 "
Cross section of one conductor	44.2 sq. "
Cross section of all parallel conductors	44.2 " "
Resistance of one phase at 60°	0.33 ohm.
Ohmic drop per phase per ampere	0.33 volt
Ohmic drop per phase at full load	32.6 "
Ohmic drop in per cent. of pressure per phase	1.13%

APPENDIX I.

Derivation of the tables set forth in Table I., and consideration of the general solution for any wave-form of electromotive force and current.

We have considered the case of armature interference due to a single conductor per pole, traversed by a constant current of i amperes, the conductor occupying a fixed position opposite the pole. (See Figs. 3 to 6.) But of course the occurrence in a dynamo consists in the flow of an *alternating* current in the conductor and the conductor moves past the pole at a rate corresponding to the frequency of this alternating current. Hence the amount of the interference of the armature magnetomotive force instead of being constant, varies from instant to instant. The magnetic flux will tend to respond to these variations in the armature magnetomotive force, but in so far as it responds, it generates eddy currents, so that the amplitude of these periodic variations in the magnetic flux is very small in comparison with the amplitude of the periodic variations in the total magnetomotive force. Thus it is justifiable to assume a mean magnetic flux corresponding to the mean total magnetomotive force. For various symmetrically situated positions of the conductor, we calculate the armature interference in the manner already illustrated and take a mean of these results for the final value. We shall now explain the derivation of this mean value for the case of a single-phase alternator with one slot per pole, on the assumption of a sine curve of current.

If we let the slot contain $2n$ conductors, we have n ampere-turns per pole. Letting i denote the effective armature current then evidently:

$n i \sqrt{2}$ = maximum armature ampere-turns per pole. Let us subdivide the pitch into 10 sections corresponding to the values

$$x = 0, \quad x = \frac{\tau}{10}, \quad x = 2 \frac{\tau}{10}, \text{ etc.,}$$

and let us first consider the case where maximum current is reached when the conductor reaches mid-pitch position. One sees at once that in this case the total number of magnetic lines is not affected by the armature interference, *i.e.*, the *demagnetizing* ampere-turns are equal to zero. Hence, in our formula (see page 188 and foot-note).

$$y = \frac{1}{2} \frac{x(b-x)i}{A b - (i b/2) + x i}$$

Since we have two n conductors for every one conductor of the elementary case, the formula now reads

$$y = \frac{1}{2} \frac{x(b-x) i \times 2n}{A b - n i b + 2x i n}$$

or, reduced

$$y = \frac{x(b-x) i n}{A b - n i b + 2x i n}$$

the denominator, which as we have seen, represents the entire surface, remains constant. In order to derive the average value of the armature *distortion* we have only to consider the variable numerator.

$$x(b-x) i n$$

The calculation can best be arranged in tabular form and this is done in Table A for the case of 50% pole-pitch, n turns per pole and one slot per pole.

TABLE A.

CALCULATION OF ARMATURE DISTORTION FOR THE CASE OF A UNI-SLOT ALTERNATOR WHERE MAXIMUM CURRENT IS REACHED WHEN THE CONDUCTORS OCCUPY THE MID-POLE POSITION.

Ratio of Pole-arc to Pitch Equals 50%

Distance from Centre of the Armature Magnetomotive Force to Mid-pole Position equals 0.

X Distance of group of conductors from mid-pole position.	$b - X$	Magnetomotive force of one group of con- ductors, in ampere- turns, at different positions.	$x(b-x) i n$ [the product of the values in the first three columns.]
0	$5\tau/10$	$n i \sqrt{2} \times 0.71$	0
$1 \times \tau/10$	$4 \times \tau/10$	$n i \sqrt{2} \times 0.89$	$n i \sqrt{2} \cdot 3.55 (\tau/10)^2$
$2 \times \tau/10$	$3 \times \tau/10$	$n i \sqrt{2} \times 0.99$	$n i \sqrt{2} \cdot 5.92 (\tau/10)^2$
$3 \times \tau/10$	$2 \times \tau/10$	$n i \sqrt{2} \times 0.99$	$n i \sqrt{2} \cdot 5.92 (\tau/10)^2$
$4 \times \tau/10$	$1 \times \tau/10$	$n i \sqrt{2} \times 0.89$	$n i \sqrt{2} \cdot 3.55 (\tau/10)^2$
$5 \times \tau/10$	$0 \times \tau/10$	$n i \sqrt{2} \times 0.71$	0

In Table A the distorting effect of the component group of conductors when lying under the pole face, has been estimated. It

has already been mentioned that the conductors when not lying under the pole face, exert no distorting influence; hence we obtain the average value for

$$x(b-x)n i$$

by adding together the six values in the last column of Table A, and dividing by 10, the total number of sections into which the pitch, τ , has been subdivided.

This average value is

$$1.9 i n \sqrt{2} (\tau/10)^2 = 0.027 i n \tau^2$$

The magnetic centre has therefore been shifted by the amount

$$\begin{aligned} y &= \frac{0.027 i n \tau^2}{A \cdot b} \\ &= \frac{0.027 i n \tau^2}{0.5 A \tau} \\ &= 0.054 \left(\frac{i n}{A} \right) \tau \end{aligned}$$

We must next proceed to consider the case where the centre of the group of armature conductors is at a distance $\tau/10$ from the pole centre at the instant when maximum current flows. Thus it now becomes necessary to consider the alteration not only in the form of the flux distribution but also in its amounts.

The change in magnitude, $i/2$ the armature demagnetization is dependent upon the expression

$$(b-2x)n i^*$$

With reference to Table A we have stated that the conductors only cause a distortion of the field when lying under the pole face, and have hence considered only these positions of the conductors in estimating the distortion. But in estimating, the decrease in the total flux, armature conductors in all positions have to be taken into account. One sees this best by considering Fig. 6 and 10. x is taken as positive in the direction from A to B . (Fig. 10). We may integrate from A to D or from one to the next of any other two points separated from one another by a distance equal to the pitch. In all cases where these conditions are complied with, the same result will be obtained. The plan pursued in deriving the following Tables has been to integrate between points C and B . $b i$ is derived by

* $(b-2x)n i$ is the area by which the original area $A b$ is diminished by the armature demagnetization. This is evident from Fig. 5.

calculating the mean magnetomotive force in ampere-turns exerted by the armature conductors in moving from B to C .

BC is divided into 10 parts and as we know that the maximum value of the sine wave of current occurs when the conductor is distant by $\tau/10$ from the mid-pole position, one can readily derive the corresponding values for all the other positions and thus obtain the mean value, which is

$$0.400 (i n) \tau$$

The value $2 x n i^*$ must of course also be obtained from the mean of this same range of positions, *i.e.*, from B to C , x being taken as positive in the direction AB from A . But the influence of the conductors when lying between A and C is evidently zero, since the air-gap may be taken as infinitely great. Hence, we have, just as in Table A, to consider only the conductors lying directly under the pole-arc.

So we again take ten symmetrically-situated positions, of which only the values for the five lying between A and B need to be calculated, while in the remaining positions

$$2 x n i = 0$$

TABLE B.

CALCULATION OF $2 x n i$ IN OBTAINING THE ARMATURE DEMAGNETIZATION FOR THE CASE WHERE MAXIMUM CURRENT IS REACHED WHEN THE CONDUCTORS OCCUPY A POSITION DISTANT BY $\tau/10$ FROM MID-POLE POSITION.

Distance of group of conductors from mid-pole position	Magnetomotive force of one group of conductors, in ampere-turns, at different positions.	$2 x n i$, the product of the values in the first two columns.
0	$i n \sqrt{2} \times 0.89$	0
$\tau/10$	$i n \sqrt{2} \times 0.99$	$0.099 \sqrt{2} (n i) \tau$
$2 \tau/10$	$i n \sqrt{2} \times 0.99$	$0.198 \sqrt{2} (n i) \tau$
$3 \tau/10$	$i n \sqrt{2} \times 0.89$	$0.267 \sqrt{2} (n i) \tau$
$4 \tau/10$	$i n \sqrt{2} \times 0.71$	$0.284 \sqrt{2} (n i) \tau$
$5 \tau/10$	$i n \sqrt{2} \times 0.455$	$0.227 \sqrt{2} (n i) \tau$

**i.e.*, $2x$ (armature ampere-turns per pole).

A summation of the values in Table B gives us

$$1.36 (n i) \tau$$

Hence, the mean value of $2 x n i$ is

$$\frac{1.36 (n i) \tau}{10} \\ = 0.136 (n i) \tau$$

and we at once obtain the distortion as

$$(b - 2x) n i = 0.400 (n i) \tau - 2 x 0.136 (n i) \tau \\ = 0.128 (n i) \tau$$

The shifting of the magnetic centre (*i.e.*, the armature distortion) is calculated just as in Table A, and as it is only the final results which are of interest, this calculation will not be repeated here. The results of these calculations are brought together in Table C.

TABLE C.
POLE ARC = 50 PERCENT OF PITCH.

ϕ^1 Distance from pole centre to the position where the current in the armature coil is a maximum	Decrease in flux expressed by $(b - 2x) n i$ <i>i.e.</i> , the armature demagnetization.	Corresponding values for a sine curve assumption.	Amount of shifting of centre of mag- netic flux expressed by $x(b - x) n i$ <i>i.e.</i> , the armature distortion.	Corresponding values for a sine- curve assumption.
		$0.41 \sin \phi'$		$0.027 \cos \phi'$
0	0	0	$0.027 (i n) \tau^2$	0.027
$\tau/10$	$0.128 (i n) \tau$	0.127	$0.0254 (i n) \tau^2$	0.0256
$2 \tau/10$	$0.24 (i n) \tau$	0.241	$0.0217 (i n) \tau^2$	0.0219
$3 \tau/10$	$0.33 (i n) \tau$	0.331	$0.0158 (i n) \tau^2$	0.0159
$4 \tau/10$	$0.39 (i n) \tau$	0.404	$0.0079 (i n) \tau^2$	0.0084
$5 \tau/10$	$0.41 (i n) \tau$	0.41	0	0

As one sees from the table, the agreement with the sine curve is practically perfect, and we are fully justified in drawing the conclusions expressed in the two following equations:

$$(b - 2x) n i = 0.41 (n i) \tau \sin \phi' = \text{armature demagnetization.}$$

$$x(b - x) n i = 0.027 (n i) \tau^2 \cos \phi' = \text{armature distortion.}$$

In the same way the corresponding values for a pole-arc equal to 70% of the pitch, have been found to be

$$(b - 2x) n i = 0.52 (n i) \tau \sin \phi' = \text{armature demagnetization.}$$

$$x(b - x) n i = 0.0707 (n i) \tau^2 \cos \phi' = \text{armature distortion.}$$

We have now arrived at the stage where we may drop the original assumption of a magnetic material without reluctance, and we will examine into the alterations thereby involved: up to this point we have reckoned throughout on the basis of the magnetic flux having only to cross the air-gap, so far as relates to the reluctance encountered. Now, those magnetic lines which must also traverse magnet core and yoke will thereby have to encounter a much greater reluctance than we have up to this point assumed.

Much the simplest way of taking account of this influence, is to alter the expressions from magnetic flux to magnetomotive force. It should be observed that this only applies to that portion of the magnetic flux which traverses magnet and yoke; for that portion which only brings about a shifting of the magnetic field, the retention of the magnetic lines is correct. Nevertheless, in order to preserve uniformity in expression we shall also transfer the latter into equivalent magnetomotive force, employing, *not* the total field magnetomotive force A but the magnetomotive force A^1 (in ampere-turns), which is necessary to drive the magnetic flux across the air-gap. That portion of the armature magnetomotive force which acts to change the magnitude of the magnetic flux is denoted by armature demagnetization, and that which acts to change its position, by armature distortion.

Returning now to the example which we have been considering, we have

Armature demagnetization	(for $b = 0.5 \tau$)	$= 0.82 (i n) \sin \phi'$
"	"	(for $b = 0.7 \tau$) $= 0.75 (i n) \sin \phi'$
" distortion,	(for $b = 0.5 \tau$)	$= 0.108 (i n) \cos \phi'$
"	"	(for $b = 0.7 \tau$) $= 0.202 (i n) \cos \phi'$

While the armature demagnetization must be deducted directly from the field magnetomotive force, one employs the armature distortion to determine the displacement of the magnetic centre, expressing this either in the form:

$$\gamma = \frac{\text{Armature distortion}}{\text{Gap ampere-turns}} \times \tau/2$$

or in degrees:

$$\beta = \frac{\text{Armature distortion}}{A^1} \times 90^\circ$$

or,

$$\beta = \frac{\text{Armature distortion}}{\text{Gap ampere-turns}} \times 90^\circ$$

[COMMUNICATED AFTER ADJOURNMENT BY COMFORT A. ADAMS.]

Note:—Vectors are indicated by bold-faced capitals.

In connection with Mr. Steinmetz's very neat and compact treatment, the following graphical representation may be of interest.

Assume that the reluctance of the main magnetic circuit is constant and the same in all radial directions. Reduce all secondary quantities to primary turns, and at first, neglect primary resistance and core loss; these may be easily taken into account later.

Referring to Fig. 1, which is a time vector diagram:

I_1 = primary current and m.m.f.

I_2 = secondary current and m.m.f.

$I_1' = I_1 \cos \beta$ = the component of the primary m.m.f. in the secondary axis, and

$I_2' = I_2 \cos \beta$ = the component of the secondary m.m.f. in the primary axis, where

β = the angle between the two axes, determined by the position of the brushes.

$J_1' = I_1 + I_2 \cos \beta$ = the resultant m.m.f. along the primary axis;

ϕ_1' = the corresponding flux.

$E_1' = j x_0 J_1'$ = the corresponding primary e.m.f. in quadrature with ϕ_1' , where x_0 is the exciting reactance.

$\phi_1' \phi_1$ = the primary leakage flux, in phase with and proportional to I_1 :

$\overline{E_1' E_1} = j I_1 x_1$ = the corresponding primary drop due to the leakage reactance, x ;

ϕ_1 = total primary flux: (1)

Draw $\overline{J_1' A}$ parallel and proportional to $\phi_1' \phi_1$, then

$\overline{OA} = J_1$ is the current which would produce the flux ϕ_1 in the main magnetic circuit. It is the total equivalent exciting current in the primary axis.

$E_1 = j x_0 J_1$ = total primary inductive e.m.f., proportional to ϕ_1 , and in quadrature therewith.

$\overline{E_1 E_0} = I_1 r_1$ = the ohmic drop in primary, and

E_0 = the impressed e.m.f. For the present $I_1 r_1$ will be neglected and E_1 will be assumed equal to E_0 , and constant

ϕ_1 and J_1 are then constant for constant E_1 .

$J_2' = I_2 + I_1 \cos \beta$ = resultant m.m.f. along secondary axis;

ϕ_2' = the corresponding flux; and

$E_2' = -j x_0 J_2 =$ the corresponding induced e.m.f.;

$\phi_2' \phi_2 =$ the secondary leakage flux; and

$E_2' E_2 = -j I_2 x_2 =$ the corresponding e.m.f.

$\phi_2 =$ the total secondary flux;

$J_2 =$ the equivalent exciting current.

$E_2 = -j x_0 J_2 =$ the corresponding e.m.f.

(1a)

$OS = I_2 r_2 =$ secondary ohmic drop.

$ST = j I_2 x_2 = E_2 E_2' =$ secondary leakage drop, where r_2

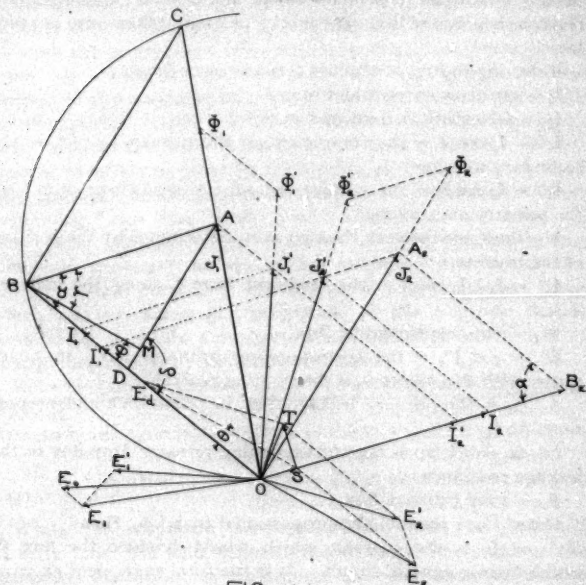


FIG. 1.

and x_2 are the secondary resistance and leakage reactance respectively.

Let ϕ_d = the dynamic flux perpendicular to the secondary axis and produced entirely by the component $I_1 \sin \beta$, of the primary m.m.f., since the secondary m.m.f. is perpendicular to that direction. Then the dynamic e.m.f. induced by the rotation of the armature, through this flux will be:

$E_d = a x_0 I_1 \sin \beta$ in phase with I_1 , where a is the speed in per cent of synchronism. (2)

$$\begin{aligned} E_d + E'_2 &= \overline{OT} = I_2 Z_2 \text{ or} \\ E_d + E_2 &= \overline{OS} = I_2 r_2 \text{ and} \\ a x_0 I_1 \sin \beta - j x_0 J_2 &= I_2 r_2 \end{aligned} \quad (3)$$

Complete the parallelograms $\overline{OT}_2 A B$ and $\overline{OI}_1' A_2 B_2$.

Let: $\mathcal{R}_0$ = reluctance of main magnetic circuit;

$\mathcal{R}_1$ = reluctance of primary leakage circuit;

$\mathcal{R}_2$ = reluctance of secondary leakage circuit.

$$\text{Then: } \mathcal{R}_0 \equiv \frac{J'_1}{\phi'_1} = \frac{J_1}{\phi_1} = \frac{J'_2}{\phi'_2} = \frac{J_2}{\phi_2} = \frac{A J'_1}{\phi_1 \phi'_1} = \frac{A_2 J'_2}{\phi_2 \phi'_2}$$

$$\mathcal{R}_1 \equiv \frac{I_1}{\phi'_1 \phi_1} \quad \mathcal{R}_2 \equiv \frac{I_2}{\phi'_2 \phi_2}$$

$$\frac{\overline{OB}}{I_1} = \frac{\mathcal{R}_0 + \mathcal{R}_1}{\mathcal{R}_1} = \frac{x_0 + x_1}{x_0} = \nu_1, \text{ the primary leakage coefficient} \quad (4)$$

and

$$\frac{\overline{OB}_2}{I_2} = \frac{\mathcal{R}_0 + \mathcal{R}_2}{\mathcal{R}_2} = \frac{x_0 + x_2}{x_0} = \nu_2, \text{ the secondary leakage coefficient} \quad (4a)$$

Then

$$\overline{OB} = \nu_1 I_1 \quad (5)$$

and

$$\overline{OB}_2 = \nu_2 I_2 \quad (5a)$$

$$J_1 = \nu_1 I_1 + I_2 \cos \beta \quad (6)$$

$$J_2 = \nu_2 I_2 + I_1 \cos \beta \quad (6a)$$

Draw $\overline{AD}$ parallel to J_2 and $\overline{BM}$ perpendicular to $\overline{AD}$. In the triangle $\overline{OAD}$, $\overline{OA} = J_1$ is constant, and angle $\overline{ODA} = \delta = 90^\circ + \theta$, where θ is the small angle between E_d and E_2 . It may be easily determined as follows: Express I_1 in terms of J_2 , it is:

$$I_1 = J_2 \frac{r_2 + j x_0 \nu_2}{r_2 \cos \beta + a x_0 \nu_2 \sin \beta} \quad (7)$$

$$\text{then } \tan (J_2 I_1) = \cot \theta = \frac{x_0 \nu_2}{r_2}$$

$$\text{and } \tan \theta = \frac{r_2}{\nu_2 x_0} = \frac{r_2}{x_0 + x_2} \text{ which is constant.} \quad (7a)$$

Therefore $\angle \delta = 90^\circ + \theta = \text{constant}$, and the point $\overline{D}$ will always fall on the arc of a circle through $\overline{O D A}$.

Draw $\overline{B C}$ parallel to $\overline{D A}$ and $\mathbf{J}_2$; then $\overline{O C}/\overline{O A} = \overline{O B}/\overline{O D}$ but $\overline{O B} = \nu_1 I_1$

$$\text{and } \overline{O D} = \overline{O B} - \overline{B D} = \nu_1 I_1 - \frac{I_1 \cos \beta}{\nu_2} = \nu_1 I_1 \left[1 - \frac{\cos^2 \beta}{\nu_1 \nu_2} \right]$$

$$\text{Therefore } \frac{\overline{O C}}{\overline{O A}} = \frac{1}{1 - \frac{\cos^2 \beta}{\nu_1 \nu_2}} = \frac{1}{\sigma}$$

where

$$\sigma = 1 - \frac{\cos^2 \beta}{\nu_1 \nu_2} \text{ is the leakage factor.} \quad (8)$$

$$\text{Then } \overline{O C} = \frac{\overline{O A}}{\sigma} = \frac{I_1}{\sigma} \text{ and is constant.} \quad (9)$$

Thus, since angle $\overline{O B C} = \delta = \text{constant}$, the locus of $\overline{B}$ is the circular arc $\overline{O B C}$. But $\overline{O B} = \nu_1 I_1$ and $\overline{B A} = I_2 \cos \beta$, i.e., proportional to I_1 and I_2 respectively. The triangle $\overline{O B A}$ thus shows clearly the relative magnitudes and phases of I_1 and I_2 , for the various positions of B on the arc $\overline{O B C}$.

SPEED.

The different positions of B correspond to different speeds and to different values of the angle γ . There is therefore some relation between the speed a and the angle γ . But as the latter is the angle between $\mathbf{E}_2$ and $\mathbf{I}_2$, its value is readily found, thus; express $\mathbf{I}_2$, in terms of $\mathbf{E}_2$; it is

$$\mathbf{I}_2 = \mathbf{E}_2 \frac{\cos \beta + j a \sin \beta}{r_2 \cos \beta + a x_0 \nu_2 \sin \beta} \quad (10)$$

$$\text{then } \tan(\mathbf{E}_2 \mathbf{I}_2) = \tan \gamma = a \tan \beta \quad (11)$$

i.e., directly proportional to the speed, or

$$a = \frac{\tan \gamma}{\tan \beta} \quad (11a)$$

It should be noted that the scale according to which $\tan \gamma$ is a measure of the speed, depends upon the brush angle β .

There are several linear methods of representing the speed, but the angular method is more convenient for the present purpose.

Referring to Fig. 2, extend $\overline{BM}$ until it intercepts the large circle at $\overline{N}$; draw $\overline{NC}$, $\overline{NA}$, $\overline{B_0}$, and $\overline{OB_0}$. Then

$\angle NCO = \angle NB_0O = \theta$, being all inscribed in the same arc $\overline{ON}$.

$\angle NBC = 90^\circ \therefore \overline{NC}$ is a diameter of circle $\overline{OBC}$.

Draw $\overline{Ob}$, making angle θ with $\overline{OA}$; then b is the center of the circle $\overline{OBC}$.

As B moves around to the right, γ and the speed decrease, until $\alpha = \theta$, when γ and the speed are zero. Thus B_0 corresponds to $\alpha = 0$, $\overline{OB_0}$ is proportional to the primary and $\overline{B_0A}$ to the secondary short-circuit current.

TORQUE.

The dynamic power is

$$P_d = E_d I_2 \cos \alpha \quad (12)$$

where

$$\alpha = \gamma + \theta. \quad (13)$$

The torque, in synchronous watts, is then

$$T = (1/a) E_d I_2 \cos \alpha \quad (14)$$

or substituting from equation (2)

$$T = x_0 I_1 I_2 \sin \beta \cos \alpha \quad (14a)$$

Draw $\overline{AH}$ perpendicular to $\overline{OB}$, then

$$\overline{HB} = I_2 \cos \beta \cos \alpha$$

and since

$$\overline{OB} = \nu_1 I_1$$

$$T = \overline{OB} \times \overline{HB} \frac{x_0 \tan \beta}{\nu_1} *$$

Thus the torque is proportional to the product of $\overline{OB}$ and $\overline{HB}$ for any given brush position, but the constant of proportionality varies with the brush position.

The locus of the point H is the semicircle $\overline{OHA}$, since $\angle OHA = 90^\circ$.

The Torque Efficiency, or torque per ampere, may be readily obtained by substituting for $\overline{OB}$ and $\overline{HB}$, in eq. 15, their values in terms of I_1 ; thus,

*NOTE.—A very simple and elegant method of representing the torque by a single line, is given by Dr. Th. Lehmann, in *L'Eclairage Electrique*, for February 13, 1904.

$$T = I_1^2 \frac{x_0 \sin \beta \cos \beta}{\nu_2} \left[1 - \frac{r_2}{r_2^2 + \nu_2^2 x_0^2} (r_2 + \nu_2 x_0 a \tan \beta) \right]$$

or, since r_2^2 is ordinarily negligible with respect to $\nu_2^2 x_0^2$

$$T = I_1^2 \frac{x_0 \sin \beta \cos \beta}{\nu_2} (1 - a \tan \theta \tan \beta) \quad (16)$$

Again, a $\tan \theta \tan \beta$ is very small at ordinary speeds and we have approximately:

$$T = I_1^2 \frac{x_0 \sin \beta \cos \beta}{\nu_2} \quad (16a)$$

i.e., the torque is approximately proportional to the square of the current. It also appears from this last equation that the *maximum torque efficiency* corresponds to a brush angle $\beta = 45^\circ$. This, however, is not the angle corresponding to the maximum torque or the highest power-factor, as will appear later.

MAXIMUM SPEED.

As B moves to the left the torque decreases and speed increases until $\bar{B}H$, and thus the torque vanishes at B_m , which corresponds to the maximum possible speed. At this point $\alpha = 90^\circ$ and $\gamma = 90^\circ - \theta$; but since θ is, under normal conditions, very small, $\tan \gamma$ and thus the speed, is very large, much beyond the safe mechanical limit as well as that of commutation.

POWER-FACTOR.

The angle ϕ (between E_1 and I_1) decreases steadily from standstill to maximum speed, as B moves from B_0 to B_m , and the power-factor increases accordingly. The factors which affect ϕ for any given speed will be considered later.

Eliminating between equations (1) (2) (3) and (6);

$$I_1 = \frac{E_1}{x_0} \frac{\nu_2 x_0 - j r_2}{\nu_1 r_2 + a x_0 \sin \beta \cos \beta + j x_0 \sigma \nu_1 \nu_2}$$

$$\tan \phi = \frac{\frac{r_2^2 + \sigma x_0^2 \nu_2^2}{x_0 \nu_2 (1 - \sigma)} + a r_2 \tan \beta}{r_2 + a x_0 \nu_2 \tan \beta} = \frac{\tan \theta + \frac{\sigma}{\tan \alpha}}{1 - \sigma} \quad (17)$$

As θ is normally very small, we have approximately

$$\tan \phi = \frac{\sigma}{(1 - \sigma) \tan \gamma} = \frac{\sigma}{a (1 - \sigma) \tan \beta} \quad (17a)$$

which is inversely proportional to the speed. Mr. Steinmetz has given one explanation (page 85) why the power-factor does not in fact increase with the speed beyond a certain limit, but reaches a maximum and then falls off.

PRIMARY POWER.

$P_1 = E_1 I_1 \cos \phi$ is proportional to the altitude of the triangle OBA , (since E_1 is assumed constant), and its maximum value occurs when B is at the top of the circle OBA .

The circle diagram¹, Fig. 2, is thus a great help in picturing the general relations of the several variables (currents, power-factors, speed, torque, and power), and the manner of their variation.

It is also very useful in tracing the effect of changes in the constants of the motor, as will appear from what follows.

IMPRESSED ELECTROMOTIVE FORCE.

Since each line of the diagram is proportional to E_1 , other things being equal, the currents will vary directly with E_1 and the torque and power with E_1^2 .

PRIMARY RESISTANCE.

If E_1 is assumed constant, $E_o (= E_1 + I_1 r_1)$, the real impressed e.m.f., must vary slightly; and since the locus of the extremity of I_1 is a circle, the locus of the extremity of $I_1 r_1$ is a similar circle, as indicated in Fig. 2.

But practically, E_o would be kept constant and E_1 would vary, decreasing slightly as I_1 increases, while the whole diagram shrinks in the same proportion. Otherwise the effect of the primary resistance is to throw E_o more nearly into phase with I_1 and thus to increase the power-factor.

CORE LOSSES.

To take account of the core losses, a small energy component must be added to the primary current, which not only increases I_1 but advances its phase and improves the power-factor.

EFFECT OF VARIATION OF CONSTANTS.

Before proceeding, it will be convenient to assemble and transform a few of the equations which show the relations between the several constants and the diagram.

1. Much the same diagram has been developed by Osnos, *Elektrotechnische Zeitschrift*, October 29, 1903, and Blondel, *L'Eclairage Electrique*, November and December, 1903, but by quite different methods, and from different points of view.

$$\tan \theta = \frac{r_2}{v_2 x_0} = \frac{r_2}{x_0 + x_2} \quad (24)$$

$$\tan \gamma = a \tan \beta \quad (25)$$

$$T = OB \cdot HB \frac{x_0 \tan \beta}{v_1} \quad (26)$$

SECONDARY RESISTANCE.

A change in r_2 affects neither $\overline{OA}$, $\overline{OC}$, nor the relation between the speed and $\tan \gamma$, but it does alter the position of the center b of the circle $OB C$, since

$$b_0 b = \frac{\overline{OC}}{2} \tan \theta = r_2 \frac{E_1}{\sigma v_2 x_0^2} \quad (27)$$

i.e., an increase in r_2 means a proportional dropping down of b from $\overline{OC}$, and when $r_2 = 0$, b lies at b_0 , the circle always passing through O and C . In Fig. 3, several resistance circles are drawn, corresponding to resistances from zero to seven.

Consider the movement of B corresponding to a change of r_2 under constant speed, *i.e.*, with γ constant.

Then $\angle ABC = 90^\circ - \gamma$ and is constant, and B will move on a circular arc $\overline{ABC}$, whose center lies on the perpendicular erected at the centre of $\overline{AC}$.

Imagine B to move along one of these constant-speed circles until $\overline{BAC} = 90^\circ$, then $\overline{BC}$ will be a diameter of circle $\overline{BAC}$, and the intersection of $\overline{BC}$ with the perpendicular $\overline{m_0 m}$ will be the center of the constant speed circle in question. Moreover, since $\overline{ABC} = 90^\circ - \gamma$, $\angle ACm = \gamma$. Thus, $\overline{m_0 m}$ is directly proportional to the speed a corresponding to the circle in question.

$$\overline{m_0 m} = \overline{m_0 c} \tan \gamma = J_1 \frac{1 - \sigma}{\sigma} a \tan \beta = \frac{E_1}{x_0} \frac{a \tan \beta}{\frac{v_1 v_2}{\cos^2 \beta} - 1} \quad (28)$$

When $a = 0$, the center falls to m_0 . Several speed circles are shown in Fig. 3.

If B falls within the semicircle $\overline{OA}$, the torque is negative, if it falls within the semicircle $\overline{AC}$, the speed is negative, and points outside of semicircle $\overline{OC}$ correspond to negative values of r_2 .

*It is understood that r_2 includes the total secondary resistance, internal and external.

whereas ν_2 which includes any external reactance connected between the brushes, may have a wide variation.

Consider then, a variation in ν_2 or x_2 . Assume that there is no external resistance between brushes, then r_2 may be neglected without seriously affecting the general results of the analysis.

Referring to the equations of page 222, a change in ν_2 or x_2 does not affect $\overline{OA}$, it does affect σ and thus $\overline{OC}$. In Fig. 4, several $\overline{OBC}$ circles are drawn, corresponding to values of x_2 , varying from +4 to -4, 0.4 being the normal value for the machine in question.

As x_2 decreases, passes through zero and increases negatively, σ decreases and passes through zero, and the point C moves out to infinity on the right and comes back on the left.

As r_2 was neglected, $\angle \overline{OBA} = \gamma$, and if the speed be maintained constant while x_2 varies, the locus of B will be a circle $\overline{OAB}$ whose center lies on the perpendicular at the center of $\overline{OA}$. If q_1 is the center of the constant speed circle corresponding to $a = 1$, then the $\angle \overline{Oq_1A} =$ twice the $\angle \overline{OB_1A}$ and $\overline{Oq_1p} = \gamma_1$. Then,

$$\frac{\overline{Op}}{\overline{p q_1}} = \tan \gamma_1 = a_1 \tan \beta$$

and

$$\overline{p q_1} = \frac{\overline{Op}}{a_1 \tan \beta} = \frac{E_1}{2 a_1 x_0 \tan \beta} \quad (29)$$

The effect of the secondary resistance will be to flatten the constant-speed circles slightly.

AIR-GAP.

An increase of air-gap means an increase in $\mathfrak{R}_0$, a decrease in x_0 , and an increase in $\overline{OA}$. An inspection of equation (20) shows that since $(1 - \cos^2 \beta)$ is ordinarily a small fraction, and since $\mathfrak{R}_1 \mathfrak{R}_2$ is large as compared with $\mathfrak{R}_0$ ($\mathfrak{R}_0 + \mathfrak{R}_1 + \mathfrak{R}_2$), σ falls only a little short of being proportional to $\mathfrak{R}_0$. Therefore, $\overline{OC}$ ($= \overline{OA} - \sigma$) is nearly independent of the air-gap.

The air-gap also effects the primary-current scale slightly (eq. 22), the torque scale to a greater extent (eq. 26), and $\tan \theta$ (eq. 24).

It is seen from (eq. 16) that the current corresponding to any given torque is otherwise approximately proportional to $\sqrt{\frac{1}{x_0}}$ or

to $\sqrt{R_0}$; thus, to double the gap would add about 40% to I_1 , and produce a considerable decrease in the power-factor. This is easily traced on the diagram by imagining $\overline{OA}$ to increase, without affecting $\overline{OC}$.

BRUSH POSITION.

Here, again, it is desirable to neglect r_2 in order to get a simpler view of the effect of changing β .

$\overline{OA}$ is unaffected, but $\overline{OC}$ increases with decreasing β .

The secondary-current scale (eq. 23), the speed scale (eq. 25), the torque scale (eq. 26) and the torque efficiency (eq. 16) are also dependent upon β .

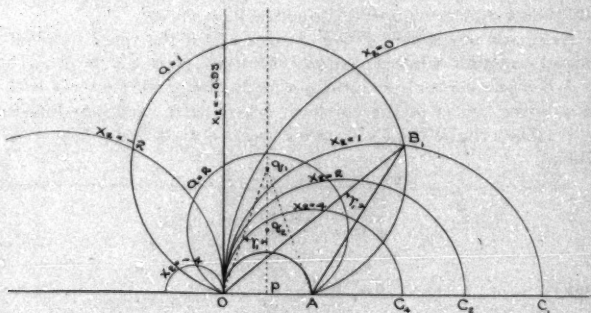


FIG. 4.

The locus of the point B with varying β and constant speed, is not a simple curve, but has been drawn in on Fig. 5 for several speeds. Circles are also shown for values of β varying from 0° to 90° .

Since all losses have been neglected, the input is equal to the output, and for any given speed the altitude of the point B is proportional to the torque; *i.e.*, if B moves along one of the constant-speed curves, the maximum torque for that speed corresponds to the highest point of the speed curve under consideration.

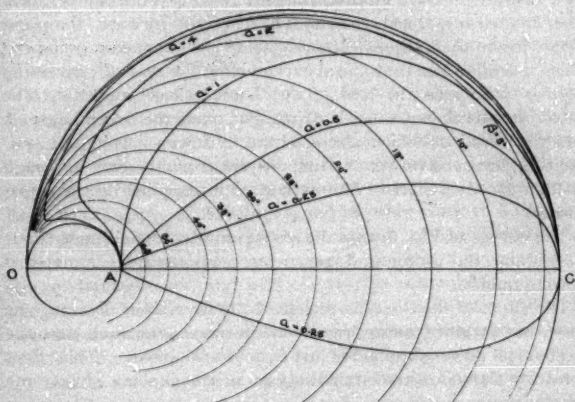
It will be observed that this maximum torque occurs with a very small brush angle β for high speeds, decreasing to 45° at standstill. This maximum torque and maximum output are obtained at the expense of a low power-factor and excessive

current, and are far beyond normal operation, except at reduced voltage. It is somewhat analogous to the maximum output obtained from a direct-current motor by weakening its field until the counter e.m.f. equals one-half of the impressed e.m.f.

The best value of β is that which gives the highest power factor; it is determined as follows, from (eq. 17a):

$$\tan \phi = \frac{\nu_1 \nu_2 - \cos^2 \beta}{a \sin \beta \cos \beta} \quad (30)$$

FIG. 5.



Placing the derivative of $\tan \phi$ with respect to β equal to zero and solving

$$\cos \beta = \sqrt{\frac{1}{1 + \sigma_0}} \quad (31)$$

which is independent of the speed.

Substituting this in (30) gives for the minimum value of $\tan \phi$

$$\tan \phi_m = \frac{2\sqrt{\sigma_0 \nu_1 \nu_2}}{a} \quad (32)$$

If $\nu_1 = \nu_2 = 1.1$, $\beta_m = 23^\circ$ and $\cos \phi_m = .703$ } for $a = 1$
 If $\nu_1 = \nu_2 = 1.05$, $\beta_m = 17^\circ$ and $\cos \phi_m = .803$ }

The less the leakage the smaller the angle β_m for maximum power-factor. Eq. (32) shows clearly the factors upon which the maximum power-factor depends.

Figs. 3, 4, and 5 together with the accompanying equations, give a fairly clean picture of the effect produced upon the operation of the repulsion motor by the variation of its several constants.

GENERATOR.

Fig. 5 lends itself readily to the tracing of the generator action of the repulsion motor.

While the machine is running at any constant speed as motor on constant-pressure circuit, connect it to a prime mover running at the same speed, then shift the brushes forward, the point B moving to the left, reaching A when $\beta = 90^\circ$, then moving out along a similar constant-speed curve below the axis, P_1 reversing sign as B crosses the axis, $\overline{OC}$. Under these conditions the power output as generator is dependent upon the brush angle, β , and the speed at which the machine is driven. It is not self-exciting, but receives its exciting current from the line, although at high speeds a part of the excitation is supplied by the rotor-current.

The curves of Fig. 5 were drawn for an ideal machine without losses, and the motor and generator portions are symmetrical in consequence.

The effect of the losses is to retard the reversal of P_1 until the speed has attained an appreciable negative value, such that the mechanical power supplied is just equal to the losses. This effect is readily shown on the circle diagram at the expense of extreme simplicity.

OBITUARY.

W. F. D. CRANE.

William Foster Day Crane was born February 12, 1865, at Elizabeth, New Jersey, and died April 28, 1903, at Orange, New Jersey, of pneumonia, after a brief illness. He was elected an associate member of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS on February 7, 1888.

Mr. Crane was prepared for college at the Newark Academy; he entered Stevens Institute with the class of '87; after three years at that college he went to Cornell University, and was graduated in 1887 with the degree of Mechanical Engineer; he remained one year longer at Cornell doing post-graduate work in electricity.

Mr. Crane's first employment, in March, 1888, was with the Baxter Motor Company, where he designed and superintended the construction of a number of constant-current and constant-potential motors and much auxiliary machinery. Later, he was engaged on the plans of extension of the plant of the Brush Electric Company of Baltimore, and in other work in Baltimore.

In March, 1889, he became electrician of the Electric Car Company of America, was engaged on the construction of storage-battery cars, and particularly the controlling apparatus and various details of these equipments. In October, 1890, he became superintendent of the New Orleans Electric Traction and Manufacturing Company; in 1891, he became manager of the electrical department of the Engineering Equipment Company of New York, and was engaged upon the design of trolley wires, insulators, and hangers. In 1892 he entered the electrical department of the H. W. Johns Manufacturing Company, where he remained until 1898; here he was employed in designing insulators and work of a similar character. In February, 1899, he became designing engineer of the Electrical Vehicle Company of Hartford, remaining with this company until January, 1901, when he entered the employment of Sanderson & Porter. From August, 1902, to the time of his death, he was connected with the business management of the American Stoker Company of New York.

Mr. Crane was a member of the New York Electrical Society; of the Cornell University Club; of the two chapters of the Chi Phi Fraternity located at Hoboken, New Jersey, and Ithaca,

New York; and of the Orange Camera Club of Orange, New Jersey. He was for several years a member of the American Society of Mechanical Engineers. Mr. Crane was not married. When his business was in or near New York he lived with his parents in Orange, New Jersey.

JOHN LEONARD KEBLER.

John Leonard Kebler, of Lawrence Park, Bronxville, New York, died very suddenly, February 2, 1904, at Albuquerque, New Mexico, from an acute intestinal disorder.

Mr. Kebler was born at Cincinnati, Ohio, September 29, 1879. His parents died when he was eight years old; after that he lived with his uncle, H. Ward Leonard.

Mr. Kebler was graduated in 1900 from Columbia University, with the degree of electrical engineer. He was elected an Associate of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS May 21, 1901.

At the age of 21, he was appointed Vice-president and General Manager of the Ward Leonard Electric Company, which position he held at the time of his death.

He was an Associate of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, a member of the Columbia Club, the Theta Delta Chi Fraternity, and various other organizations.

Mr. Kebler possessed to a rare degree the best and most lovable qualities of manhood; it would be difficult to find a young man of his age who had accomplished more, and who had more brilliant prospects. His untimely death will be greatly deplored by his numerous friends.

ACCESSIONS TO THE LIBRARY.

The following donations have been made to the Library since the last acknowledgement.

Boston Public Library:

LIST OF PERIODICAL PUBLICATIONS Currently Received by the Public Library of the City of Boston. 78 pp., 8°. Boston. 1903.

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Mr. Edison also defrayed the cost of binding or rebinding this valuable set which is complete to date, uniformly in half-morocco.

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ADVANCE COPIES INTERNATIONAL ENGINEERING CONGRESS PAPERS.

The International Engineering Congress, to be held at St. Louis, October 3d to 8th, 1904, is being organized under the auspices of the American Society of Civil Engineers. Many of the papers to be presented will be of interest to electrical engineers. Among those already promised are the following:

Turbines and Water Wheels, by PROFESSOR GARDNER S. WILLIAMS, Ithaca, N. Y.

Railroad Terminals, by ELMER L. CORTHELL, New York City.

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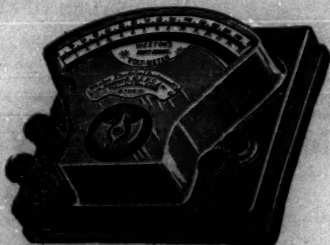
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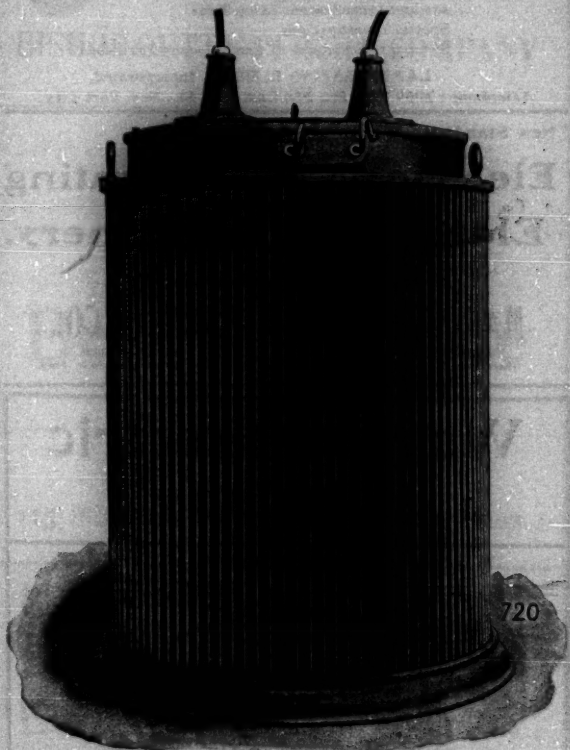
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